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A Mexican Case Study for World Water Online

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A Mexican Case Study for World Water Online

by

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Dedication

I would like to dedicate this thesis to my family: Berenice, Gonzalo, Miriam and Antonio for all the support and advice given through the years. Furthermore, to my loving grandparents: Rita, Maria and Gonzalo; and the memory of my deceased grandfather Margarito.

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I would like to thank my supervisor Dr. Maidment for his precise guidance and advice; also for sharing his vision and experience. I would like to thank my former professor, Dr. Martinez for his teaching and for encouraging me to look to a specialization in Water Resources. I would also like to thank Georges Comair for his valuable points of view and Erika Boghici for her comments and helpful disposition.

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Abstract

A Mexican Case Study for World Water Online

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The University of Texas at Austin, 2012

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World Water Online is a global system of hydrologic data. It is an integration of geospatial and temporal information across spatial scales: global, national, regional and local. This global water information system has no parallel, and its scope would be extended with the active participation of the global water community. Its consolidation depends on the accessibility of countries' databases through the system. In this study, a test case using Mexican data within World Water Online is created, applying the CUAHSI framework, web services and standards. The resulting Mexican-HIS unifies the water information for the nation regardless of data provider, improving storage practices and allowing additional querying and retrieving functionalities: World Water Online is a source of information and also a supplier of web-based processing services. In the second part of this study, a precipitation-runoff analysis using the data in the system is performed.

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Chapter 1: Introduction

1.1 Hydrology and Hydrologic Data

Hydrology is the science that studies the temporal and spatial distribution of water on the planet. The water flux results from complex phenomena and depends on the integration of globally dominated changes - such as solar cycles and hydrosphere/atmosphere interactions - into local scale physics, such as precipitation and evapotranspiration.

The water cycle (Figure 1.1) is the division of the water transport problem into several parts. Each part represents a process in which the water moves spatially or changes in physical state. In this framework e.g. we define precipitation as the flux of atmospheric water onto the land surface; runoff is the transport of water across the terrain, from higher to lower elevations, and evapotranspiration is the flux of water from the terrain, lakes, oceans and plants into the atmosphere. Water moves from one process to another in an interconnected network.

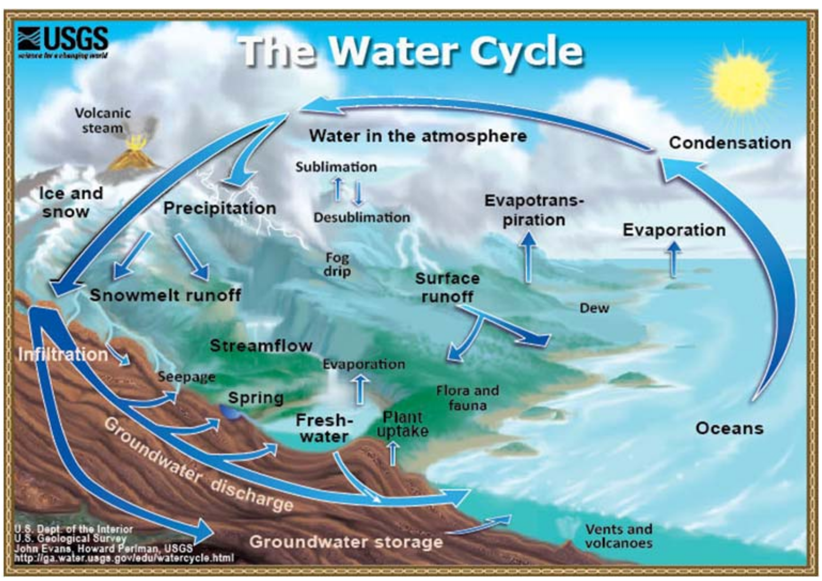

Figure 1.1: The Water Cycle (USGS, 2012)

The water cycle is a complex and thoroughly connected system. It is the set of driving processes that relocate water through time and space. The quantitative study of these processes (i.e. precipitation, evapotranspiration, runoff, etc.) can help to predict the temporal variation of water for a particular location. These estimations are necessary to provide solutions and combat challenges in water resources. They could answer, among others, the following questions: Where are the water sources of a city located, and how much water can they provide? Where should a new dam be built, and how much water will flow there? What areas of a community are more sensitive to flooding during a storm? Should we expect a drought for the upcoming years? What is the frequency of extreme (storms/droughts) hydrologic events?

Water resources engineers use theoretical and empirical models to answer these questions. The models depend on information as input or for calibration; the reliability of the model output depends completely on the ingested information. Hydrologic data results from the measurement of the different processes in the water cycle; it helps engineers support their decisions and make predictions for upcoming events. The data should be sufficient in quality and quantity, reliable, accessible and organized in a standard way.

The different institutions who manage water in various countries have created and are operating different networks of stations. Moreover, these institutions develop systems to indirectly estimate (i.e. with radar and satellite measurements) the hydrologic variables within their jurisdiction. These organizations are in charge of creating and updating their databases regularly. They may make the data available for the public.

1.2 GATHERING HYDROLOGIC DATA

Data gathering is done by different institutions and organizations. In general, these entities are formed by countries' governments. They have a wide spectrum of responsibilities, but within the legal framework they have the duty of generating hydrologic data.

In the United States, for example, the United States Geological Survey (USGS) is the organization in charge of water data at a federal level. Additionally, on a regional scale there are state-dependent organizations. For example, in Texas the Lower Colorado River Authority (LCRA) operates the stations and dams in the Lower Colorado River. The Texas Commission on Environmental Quality (TCEQ) conducts a sampling program that measures pollutants in Texas streams.

Other countries such as Mexico have more centralized sources of information. The federal government controls gathering and publishing hydrologic information, while the state offices operates and regulate the water resources. The Ministry of Environment and Natural Resources (SEMARNAT) is responsible at the federal level and it contains the National Water Commission (CONAGUA) and the Mexican Institute of Water Technology (IMTA). CONAGUA implements and manages hydrologic information networks in the country. IMTA is a research institute, it has the duty of develop and implement new technologies.

On a global scale, there is no organization (not even in the UN) with the mission of agglomerating and standardizing hydrologic data. Some efforts have been made by institutions such as the Global Runoff Data Centre (GRDC), which collects stream discharge data from different countries and republishes it. In addition, the Open Geospatial Consortium (OGC) has gathered a significant number (438) of companies, research and academic institutions, etc., in order to develop and adopt standards for internet data exchange.

1.3 SHARING HYDROLOGIC DATA

The extended use of information technologies in our everyday life has transformed the way that information is shared. We have moved from paper and hardcopies to hyperlinks, web pages and web services. Water organizations publish their data through their websites. The data is available, but each organization may use different formats and standards. Data users now confront new challenges: they have to access hydrologic data using different filters and through different systems. The process in some cases is inefficient and should be improved.

1.4 OBJECTIVES

The objective of the present work is to create and implement a Hydrologic Information System (HIS) using data from Mexico as a test case in a global system of hydrologic data called “World Water Online” (WWO).

Additionally, the data is used to create products with a higher value added than just plain information. A precipitation map for Mexico is developed. The data is also used to perform a precipitation-runoff analysis for a specific region in Mexico (Papaloapan River), which demonstrates the use and importance of a single, global, unified and standardized system.

Chapter 2: Literature and Technology Review

2.1 Geographic Information Systems (GIS)

Geographic Information Systems (GIS) are the digital map representations of geospatial features (Goodchild, 1993). Each geospatial feature is linked to tabular data that contains information. For water resources these features represent stations, drainage areas, streams, surface elevations, etc. The tabular data associated are time series, such as precipitation, discharge, etc. (Figure 2.1)

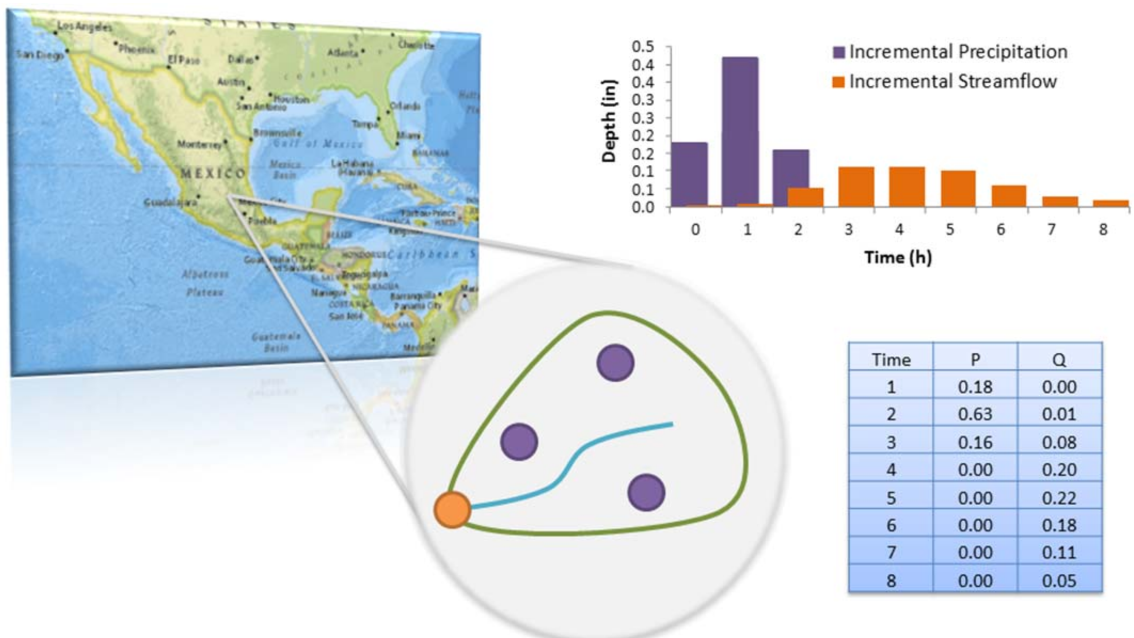

Figure 2.1: GIS and Water Resources Spatial-Data Relationships.

The exponential development of information technology of the past decades benefits GIS. It impels researchers and software developers to design complex tools, which are available through commercial or open source applications. GIS has significantly reduced mapping and calculation limitations, extending their use in practical engineering.

GIS has a relevant role in water resources, due to the spatial nature of the physical phenomena under study. GIS are used for processing and analysis of water data (Dangermond et. al, 2010) but their use is not limited to that. GIS are being used to build and share hydrologic information through the web using standardized services.

2.2 Hydrologic Information Systems (HIS)

A Hydrologic Information System (HIS) is the compilation over time and space of water data, processing tools and models that can be used in hydrologic science (Maidment, 2005). The temporal records that measure different variables (precipitation, discharge, evapotranspiration, etc.), the geospatial features that describe hydrologic elements (lakes, rivers, stations, etc.), the connectivity between elements (downstream/upstream, edges and nodes) and the models used (Precipitation-Runoff, flood level, etc.) are all parts of a HIS.

The purpose of a HIS is to, within a single system, hold water information, perform analysis using models and return results in useful ways that can be utilized in engineering applications.

2.3 Environmental Systems Research Institute (ESRI)

Since its foundation in the late 1960's; the Environmental System Research Institute (ESRI) has been developing software and sets of tools for geographic analysis. Its most recognized software, ArcGIS, is the result of years of improvements from specific project applications, leading to a product with a diverse spectrum of tools, including terrain processing, spatial analysis, statistics and mapping, among others (ESRI, 2012). ESRI has established GIS standards, developing ways to store and interchange data, such as in shapefiles and geodatabases.

In 2002, the Center for Research in Water Resources (CRWR) and ESRI developed ArcHydro. “ArcHydro is a geospatial and temporal data model for water resources” (Maidment, 2002). ArcHydro is a module within ArcGIS that provides a common structure to connect hydrologic features.

Additionally, ESRI has implemented a web-accessible mapping service called “ArcGIS Online”. ArcGIS Online is a map library, and it offers access to GIS through the web. Any user can create, upload and share their maps, as well as access maps that have been published already. ArcGIS Online represents the community of maps users.

2.4 World Water Online

The fast development of information technologies, the extended use of GIS and the constant growth of water databases motivate researchers to develop more complex and integrated HIS.

Due to the lack of a global water information system, CRWR joined the efforts of ESRI and Kisters and started developing the incipient project of a unified global water system: World Water Online (WWO). (Figure 2.2)

World Water Online is a global system of hydrologic data. It is an integration of geospatial and temporal information through all different scales: global, national, regional and local.

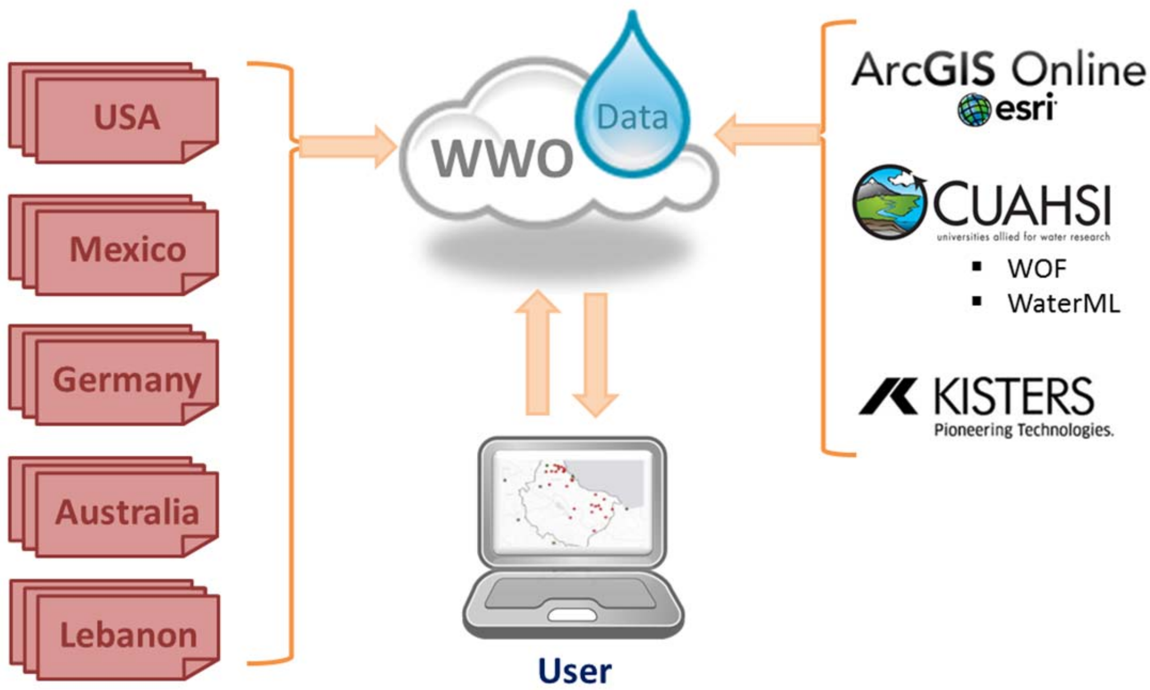

Figure 2.2: World Water Online.

The mission of WWO is to implement a single system through which hydrologic data can be accessed. The underlying idea is that each country is in charge of making its data available through WWO.

In order to encourage institutions and people to use a global water system, WWO has to prove its practical applicability for the academic and practical water resources communities. Demonstration of successful test cases will encourage more participants to join in the effort for its implementation.

For global acceptance, the system must follow pre-established and validated standards for data storage and sharing. These standards are described in the following sections.

2.5 THE CONSORTIUM OF UNIVERSITIES FOR THE ADVANCEMENT OF HYDROLOGIC SCIENCE, INC. (CUAHSI)

The Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) is the result of attempts by universities and the scientific community in the United States to assess and improve hydrologic sciences. Since 2004, the National Science Foundation (NSF) has been funding the project. CUAHSI's mission is to encourage development of and increase knowledge in water science, recognizing the central role of water for society (CUAHSI, 2012).

In the United States, one hundred and twenty five universities are members of the Consortium and seven universities have joined as affiliated members. The interest in building a network of hydrologic scientists reaches beyond the U.S. borders: nineteen international affiliates have joined, including organizations from Australia, Denmark, Slovenia, South Korea, Sweden and United Kingdom.

The creation of CUAHSI has no precedent; its projects shape and lead the future of research in hydrologic sciences. One of the leading projects of the Consortium is CUAHSI-HIS, which is used for sharing water data between the members and outside users.

2.5.1 CUAHSI-HIS

CUAHSI-HIS is a web platform used for storing, sharing and distributing hydrologic data. CUAHSI-HIS is a framework to be implemented with the use of tools developed for water data sharing. CUAHSI-HIS is focused on the transmission of water data. Its applicability starts after data is recorded digitally, and finishes when the user has access to the specific data.

It has three main components (Figure 2.3): data publication, data discovery and data access. (CUAHSI, 2012). CUAHSI-HIS provides functionality and is continuously releasing and updating tools for these components.

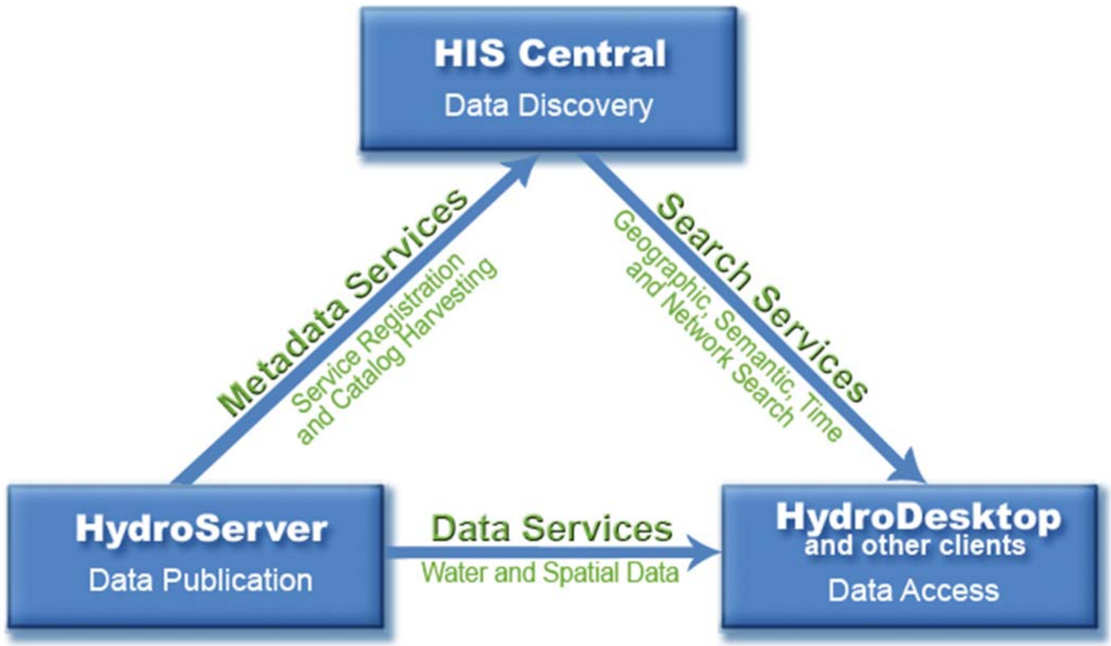

Figure 2.3: Components of CUAHSI-HIS.

Within CUAHSI-HIS, HydroServer manages the publication of data. It is the component that deals with data storage using an Observations Data Model (ODM) database (section 2.5.2). The data is published with WaterOneFlow (WOF) web services (section 2.5.3) and the data transmission uses standard Water Markup Language (WML) as the interchange scheme (section 2.5.4).

Finally, the data can be discovered through the HIS Central Metadata Catalog (section 2.5.5), and accessed using client applications: Hydrodesktop or Hydroexcel (section 2.5.6). All of these key parts of CUAHSI-HIS are described in the following sections.

2.5.2 Observations Data Model (ODM)

Observations Data Model (ODM) is a database for storing, accessing, querying and retrieving water data. It was designed to optimize access to data. ODM provides relationships through identifiers (ID): the identifiers link the stations, variables and values. (Figure 2.4)

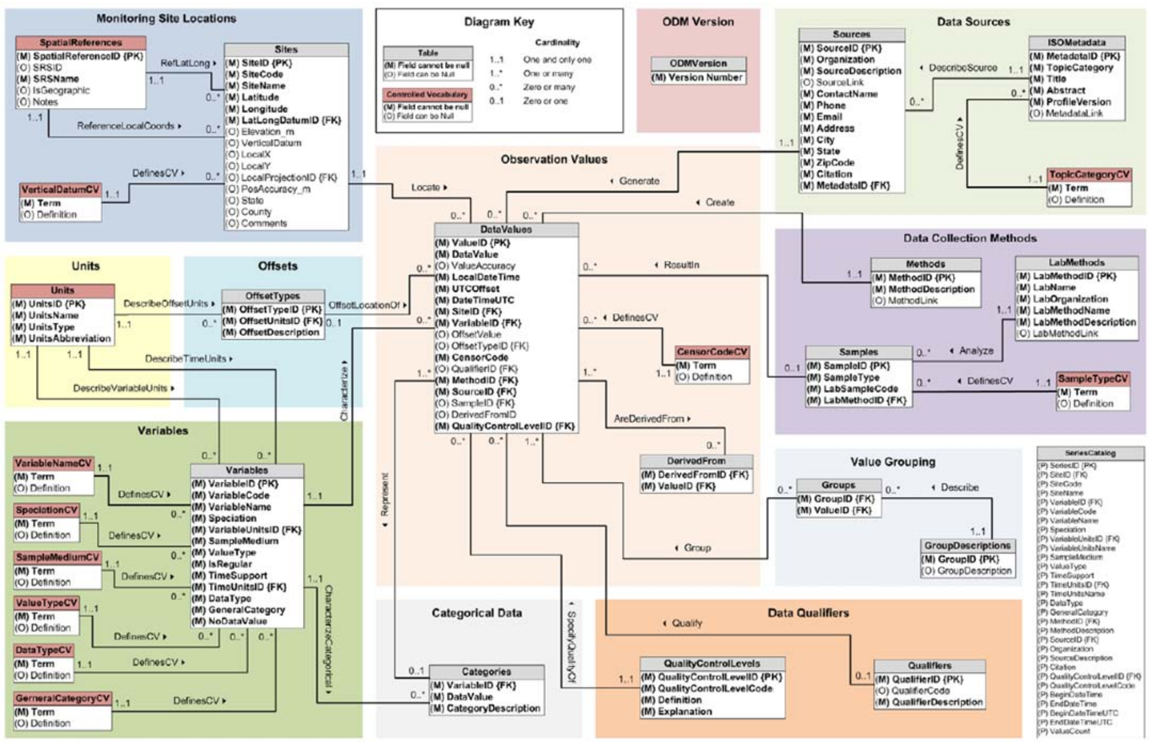

Figure 2.4: Observations Data Model Schema. (CUAHSI, 2008)

The ODM scheme provides enough information in a structured format to enhance the understanding of the information itself. ODM avoids ambiguity among different water sources and publishers by unifying different parameter characteristics through a standardize vocabulary and unique identifiers.

The three main descriptions of a hydrologic observation are time, space and measured variable (Figure 2.5). The temporal part is distinguished with a stamp of the time of occurrence. Spatially, the value is linked to a station, which has a defined geographic location. The variable corresponds to one entry in a variables table; this table has sufficient information to completely describe the variable (units, sample medium, etc), and each variable is unique.

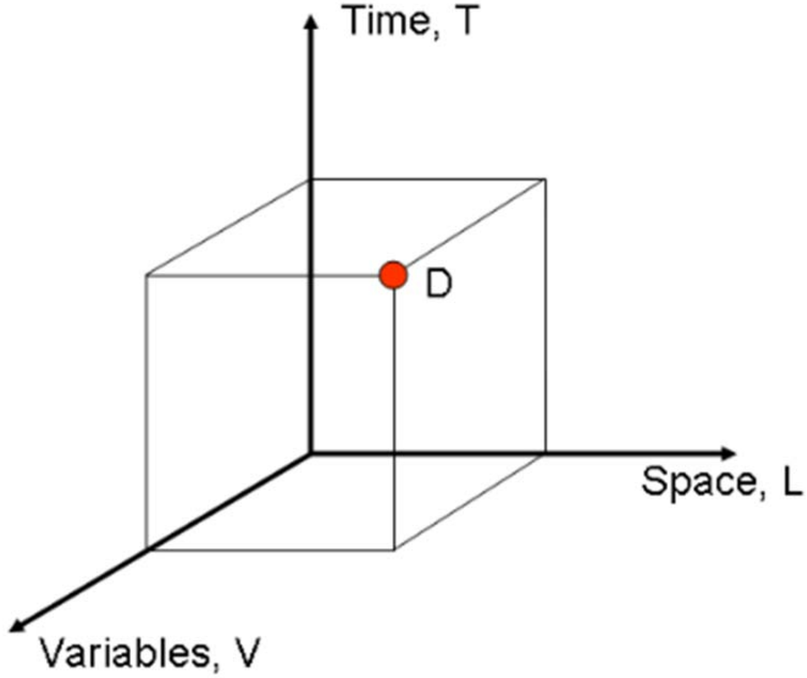

Figure 2.5: Data Cube: Time, Space and Variable (Tarboton et al. 2008).

For a single variable and a single station, all the points (red dot) will fall on the line parallel to the vertical axis (time, T): this will be a single time series. With these three fundamental variables, the observations universe for the ODM database is created.

Each hydrologic observation within the ODM has a minimum number of attributes that describe it. The information on this attributes is presented in Table 2.1. The underlying idea of the following table is to have defined positions for the required information. The table is a template and a guide for publishers and must be filled with the CUAHSI vocabulary.

Table 2.1: ODM Attributes Associated with an Observation. (Tarboton, 2008)

Attribute	Definition
Data Value	The observation value itself.
Accuracy	Quantification of the measurement accuracy associated with the observation value.
Date and Time	The date and time of the observation. (including time zone offset relative to UTC and daylight savings time factor)
Variable Name	The name of the physical, chemical, or biological quantity that the data value represents. (e.g. streamflow, precipitation, temperature)
Speciation	For concentration measurements, the species in which the concentration is expressed. (e.g., as N, or as NO3, or as NH4)
Location	The location at which the observation was made (e.g. latitude and longitude)
Units	The units (e.g. m or m3/s) and unit type (e.g. length or volume/time) associated with the variable.
Interval	The interval over which each observation was collected or implicitly averaged by the measurement method and whether the observations are regularly recorded on that interval.
Offset	Distance from a reference point to the location at which the observation was made (e.g. 5 meters below water surface)
Offset Type/Reference Point	The reference point from which the offset to the measurement location was measured. (e.g. water surface, stream bank, snow surface)
Data Type	An indication of the kind of quantity being measured (e.g. a continuous, minimum, maximum, or cumulative measurement)
Organization	The organization or entity providing the measurement.
Censoring	An indication of whether the observation is censored or not.

Table 2.1: (continued)

Data Qualifying Comments	Comments accompanying the data that can affect the way the data is used or interpreted. (e.g. holding time exceeded, sample contaminated, provisional data subject to change, etc.)
Analysis Procedure/Method	An indication of what method was used to collect the observation (e.g. dissolved oxygen by field probe or dissolved oxygen by Winkler Titration) including quality control and assurance that it has been subject to.
Source	Information on the original source of the observation. (e.g. from a specific organization, agency, or investigator 3rd party database)
Sample Medium	The medium in which the sample was collected. (e.g. water, air, sediment, etc.)
Value Category	An indication of whether the data value represents an actual measurement, a calculated value, or is the result of a model simulation.

2.5.3 WaterOneFlow (WOF) Web Services

A web service is the software part of a system that points and establishes the interchange pattern of information between two computers through a network. Web services contain pre-established methods that users can call through the web. The methods provide capabilities that give functionality to specific tasks; they are standardized ways, within web services, used to retrieve and access data.

WaterOneFlow is a web service scheme that can be used to share hydrologic data stored in an ODM database. WaterOneFlow optimizes the retrieving and querying of water data using a standard methodology. It returns an output in the same format, regardless of the provider (Whiteaker, 2010).

There are four standard methods within WaterOneFlow to access and retrieve water data:

- GetSiteInfo/GetSiteInfoObject: This method returns information about the site (name, latitude, longitude, station code, etc.).

- GetSites/GetSitesXml: This method lists the sites with their information.
- GetVariableInfo/GetVariableInfoObject: This method returns information about the variable measured (name, units, type, category, etc.).
- GetValues/GetValuesObject: This method returns the values given a location, variable and time span.

These methods exist within the WaterOneFlow service (server) and can be called by the user (client). The interchange schema between servers and clients is made in a common language: WaterML, which is explained in the following section.

2.5.4 Water Markup Language (WaterML)

Water Markup Language (WaterML) is a customization of the Extensible Markup Language (XML); the latter is an adaptable simple text format designed as an exchange language through the web (W3C, 2008).

WaterML is designed to transmit hydrologic data and metadata in a consistent format, unifying all the possibilities from different data publishers and providers. WaterML (Figure 2.6) focuses on the three main descriptors of a hydrologic observation: time, space and variable.

WaterML gives the user the basic information to understand the data without additional material (Valentine, 2009). This information is grouped in four categories, three of them corresponding to the data cube descriptions (time, space and variable) and the last one dealing with web method queries and quality control.

```
<?xml version="1.0" encoding="utf-8" ?>
- <timeSeriesResponse xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
   xmlns:xsd="http://www.w3.org/2001/XMLSchema" xmlns="http://www.cuahsi.org/waterML/1.1/">
 + <queryInfo>
 - <timeSeries>
   - <sourceInfo xsi:type="SiteInfoType">
       <siteName>PENUELITAS; GTO</siteName>
       <siteCode network="CNASMNEA" siteID="189">GT04</siteCode>
     - <geoLocation>
       - <geogLocation xsi:type="LatLonPointType">
           <latitude>21.105</latitude>
           <longitude>-100.578055</longitude>
         </geogLocation>
       </geoLocation>
       <elevation_m>1931</elevation_m>
       <verticalDatum>MSL</verticalDatum>
     </sourceInfo>
   + <variable>
   - <values>
       <value censorCode="nc" dateTime="2011-10-21T00:00:00" timeOffset="-06:00" dateTimeUTC="2011-
         10-21T06:00:00" methodCode="1" sourceCode="5" qualityControlLevelCode="-9999">1.85</value>
       <value censorCode="nc" dateTime="2011-10-21T01:00:00" timeOffset="-06:00" dateTimeUTC="2011-
         10-21T07:00:00" methodCode="1" sourceCode="5" qualityControlLevelCode="-9999">1.85</value>
       <value censorCode="nc" dateTime="2011-10-21T02:00:00" timeOffset="-06:00" dateTimeUTC="2011-
         10-21T08:00:00" methodCode="1" sourceCode="5" qualityControlLevelCode="-9999">1.85</value>
       <value censorCode="nc" dateTime="2011-10-21T03:00:00" timeOffset="-06:00" dateTimeUTC="2011-
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       <value censorCode="nc" dateTime="2011-10-21T04:00:00" timeOffset="-06:00" dateTimeUTC="2011-
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       <value censorCode="nc" dateTime="2011-10-21T05:00:00" timeOffset="-06:00" dateTimeUTC="2011-
         10-21T11:00:00" methodCode="1" sourceCode="5" qualityControlLevelCode="-9999">1.84</value>
       <value censorCode="nc" dateTime="2011-10-21T06:00:00" timeOffset="-06:00" dateTimeUTC="2011-
         10-21T12:00:00" methodCode="1" sourceCode="5" qualityControlLevelCode="-9999">1.83</value>
       <value censorCode="nc" dateTime="2011-10-21T07:00:00" timeOffset="-06:00" dateTimeUTC="2011-
         10-21T13:00:00" methodCode="1" sourceCode="5" qualityControlLevelCode="-9999">1.83</value>
       <value censorCode="nc" dateTime="2011-10-21T08:00:00" timeOffset="-06:00" dateTimeUTC="2011-
         10-21T14:00:00" methodCode="1" sourceCode="5" qualityControlLevelCode="-9999">1.83</value>
       <value censorCode="nc" dateTime="2011-10-21T09:00:00" timeOffset="-06:00" dateTimeUTC="2011-
         10-21T15:00:00" methodCode="1" sourceCode="5" qualityControlLevelCode="-9999">1.84</value>
```


Figure 2.6: WaterML Response Example.

2.5.5 HIS Central Metadata Catalog

Data publishers have the option to register their services and make them available as part of the CUAHSI-HIS network. The Central Metadata Catalog contains the information related to all the web services. After registering, the data is available for discovery and access through clients (Whitenack, 2010). CUAHSI clients, Hydrodesktop and Hydroexcel, are discussed in the following section.

2.5.6 CUAHSI Clients: Hydrodesktop and Hydroexcel

The clients are software used to discover and access data. CUAHSI-HIS has developed two clients, Hydroexcel and Hydrodesktop (Figure 2.7).

Hydroexcel is a Microsoft Excel spreadsheet. It uses Microsoft's built-in programing language VBA along with HydroObjects to download data to Excel. HydroObjects is a program class that supports a method to call and ingest data from web services (Whiteaker, 2011). Hydroexcel takes advantage of the widespread use of MS Excel, creating an easy and straightforward way to access hydrologic data.

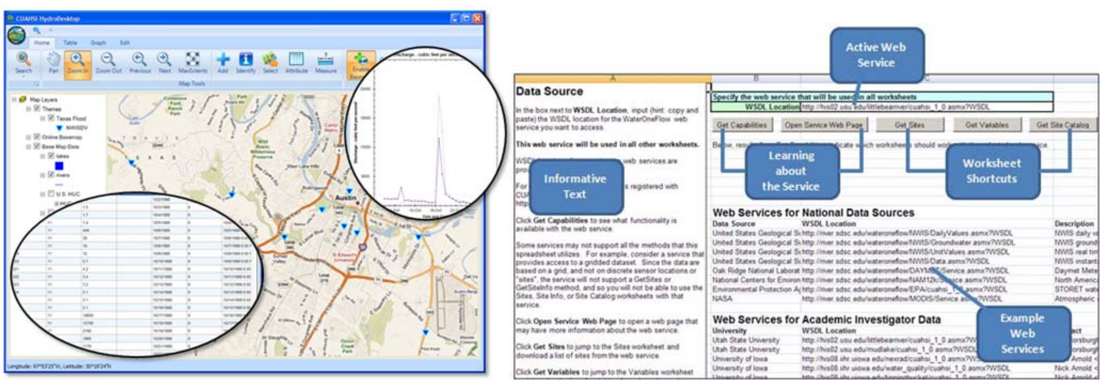

Figure 2.7: Hydrodesktop (left) and Hydroexcel (right) Interface Applications. (CUAHSI, 2012)

Hydrodesktop is a more complex and complete product. Hydrodesktop is an open source GIS software, and unlike Hydroexcel, it provides additional capabilities besides tabular data (Whiteaker, 2010).

Its mapping component geographically displays the data locations. The data can also be plotted within Hydrodesktop. These additional components improve the user visualization experience, but newcomers will need to spend time getting familiar with the application.

2.6 Hydrologic Information in Mexico

In Mexico, the Ministry of Environment and Natural Resources (SEMARNAT) is the government agency in charge of the administration, protection, conservation and restoration of all natural resources in the country. As a division of SEMARNAT, the National Water Commission (CONAGUA) is the institution in charge of administrating and preserving water in the nation. Its mission is to provide sufficiently good quality water to the public, recognizing water's vital role for development and as a public good. (SEMARNAT, 2012)

The Mexican Institute of Water Technology (IMTA) is part of CONAGUA but is a decentralized public organization. Its mission is to identify and combat the nation's water challenges through new approaches and technological development.

In this legal framework, the SEMARNAT division, CONAGUA, with support from IMTA, has the duty of implementing and managing the required networks, systems and technologies to generate sufficient water data for the nation.

The National Institute of Statistics and Geography (INEGI) is the public organization that manages historical statistical data and geographic characteristics. Due to its widely varied range of applications, it deals with data from economic parameters, population census and industrial characteristics, to hydrographic, geological and topographic maps. (INEGI, 2012)

INEGI is a diverse institution that offers support and develops products for government organizations, professionals and the public in general. Geographically, INEGI deals with the distribution and location of natural resources. Statistically, it measures the change of these resources over time.

2.6.1 CONAGUA: Hydrologic and Meteorological Data

As a main part of its mission, CONAGUA has implemented and maintains measurement and data collection networks. Not all data is accessible or even available for the public in general. CONAGUA has three networks that can be accessed through their web site: BANDAS for stream discharge, EPPREPMEX for estimated precipitation and EMA's for meteorological data.

2.6.1.1 National Dataset of Surface Water (BANDAS)

The National Dataset of Surface Water (BANDAS) is the digital system that stores, among others, mean and maximum values of stream discharge. It has 2,070 hydrometric stations across Mexico. The latest update was made in 2006 and some of the stations have entries since the late 1940's and the beginning of the 1950's. There are no official release dates for upcoming data.

The data is available through downloadable Microsoft Access or dBase (DBF) files. Each station has a unique file, containing individual tables for different time intervals (daily, monthly or yearly). The tables are structured with prefix identifiers and station IDs.

Separately, each station has a technique document (text file) with relevant information containing site description, site name, installation characteristics, drainage area, extreme values recorded, water body and geographic location. (IMTA, 2012)

The information in the BANDAS dataset is valuable but extracting it is a slow process. It lacks querying, accessing capabilities, and standard methods. Moreover, there is no link between the data and mapping services.

2.6.1.2 Rainfall Estimation and Forecasting in Mexico (EPPREPMEX)

The Rainfall Estimation and Forecasting in Mexico (EPPREPMEX) system was established in 1991. It was initially focused on the analysis of tropical cyclones. The current version can estimate rainfall for different weather systems with satellite images and radar (Figure 2.8).

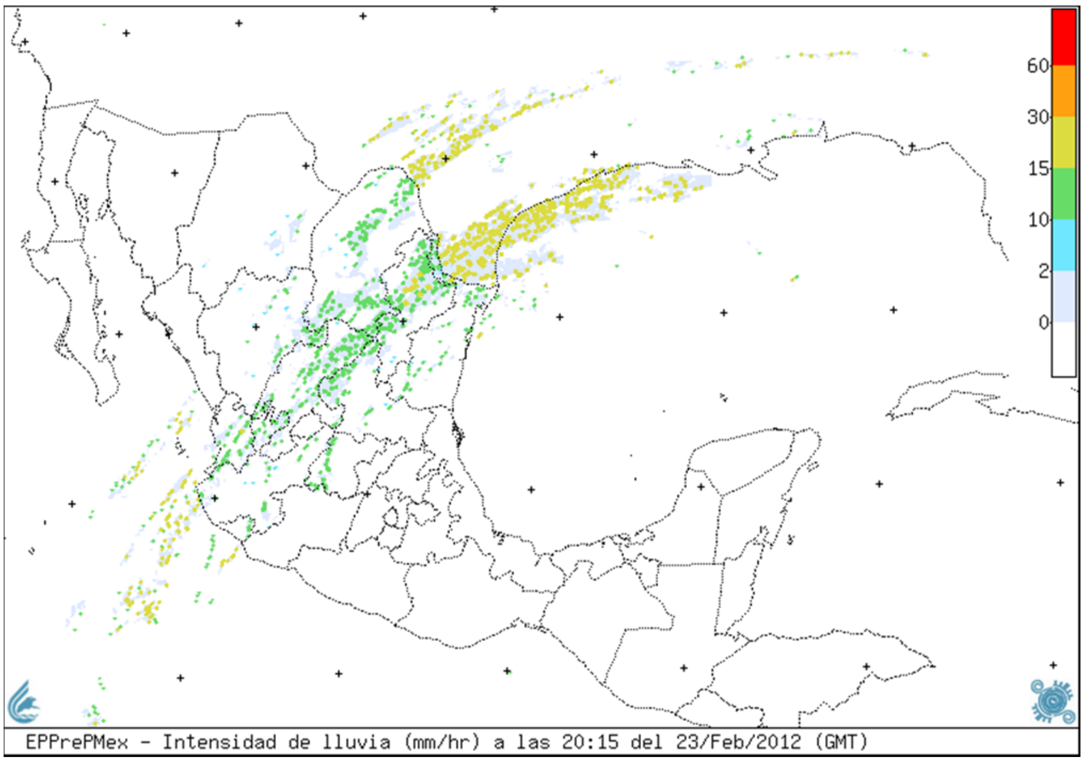

Figure 2.8: Water Intensity Map Generated with Radar-Estimated Data (CONAGUA, 2012).

The product consists of daily cumulative precipitation for a subset of 1,099 virtual stations throughout Mexico. A virtual station is a geographical fixed point in which the precipitation is estimated. The data is published as plain text files on the CONAGUA web site; usually, it can be accessed up to the last seven days. (CONAGUA, 2012)

2.6.1.3 Automatic Weather Stations Network (EMA's)

The Automatic Weather Station Network (EMA's) is a system of 493 meteorological stations. The variables measured are wind speed, gust speed, temperature, relative humidity, barometric pressure, rainfall, stage and solar radiation. The stations automatically transmit the information to CONAGUA servers. The data is available in intervals of 10 minutes, 60 minutes and daily averages.

The information is published as plain text through the CONAGUA web site. Data can be discovered geographically using a map interface (Figure 2.9); the user can zoom in to the desired location and select one station at a time. There is not a complete list of stations (CONAGUA, 2012)

Figure 2.9: Automatic Weather Stations Network (EMA's) Map Interface. (CONAGUA, 2012)

2.6.2 INEGI: Geographic data

INEGI provides two sets of information useful for water resources: the Mexican Continuum of Elevations 2.0 (CEM) and the Hydrographic Network 2.0. Both products are available to download though the INEGI web site (http://www.inegi.org.mx).

2.6.2.1 Mexican Continuum of Elevations 2.0 (CEM)

The Mexican Continuum of Elevations 2.0 (CEM) is a representation of the terrain surface elevation using a Digital Elevation Model (DEM) raster. The raster (Figure 2.10) resolution is one arc second (approximately 30m cell size) (INEGI, 2012).

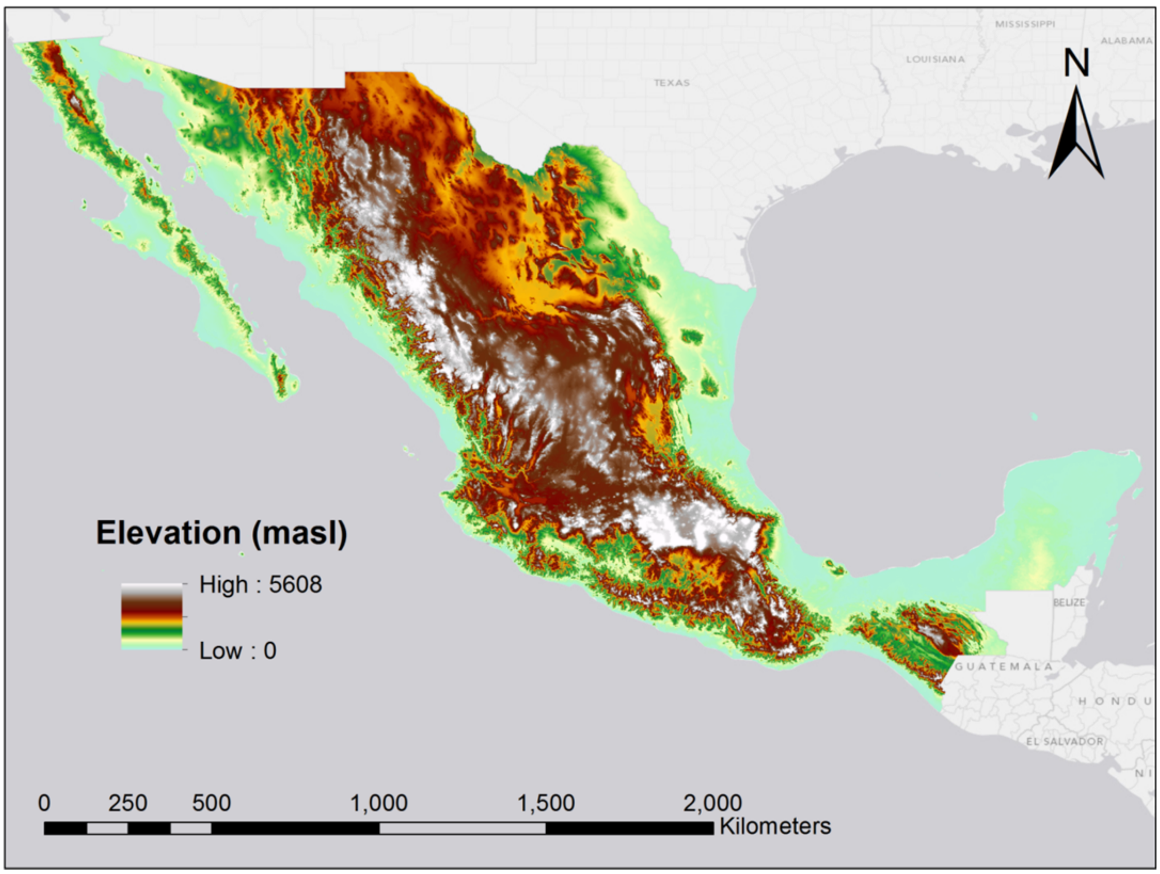

Figure 2.10: Digital Elevation Model (DEM) for Mexico.

2.6.2.2 Hydrographic Network 2.0

Hydrographic Network 2.0 contains basin and drainage area divisions for Mexico. The country is divided into three levels (Figure 2.11). The highest level division contains 37 regions, followed by 158 watersheds and 978 subwatersheds.

The streams form a topological connected network for Mexico. These were created using ArcHydro and are available as a geodatabase. Additionally, the geodatabase contains mapped water bodies in the country. The scale of the network is 1:50,000 (INEGI, 2012).

Figure 2.11: Hydrologic Units in Mexico.

2.7 PRISM Climate Group

The Parameter-elevation Regressions on Independent Slopes Model (PRISM) group was formed by Oregon State University to develop climate research and mapping services in the United States (PRISM, 2012).

The PRISM system uses point measurements of temperature, precipitation and other meteorological variables to produce raster products for the U.S. The products consist of precipitation (Figure 2.12), temperature and dew point rasters, which are published in monthly and yearly time intervals through the PRISM web site.

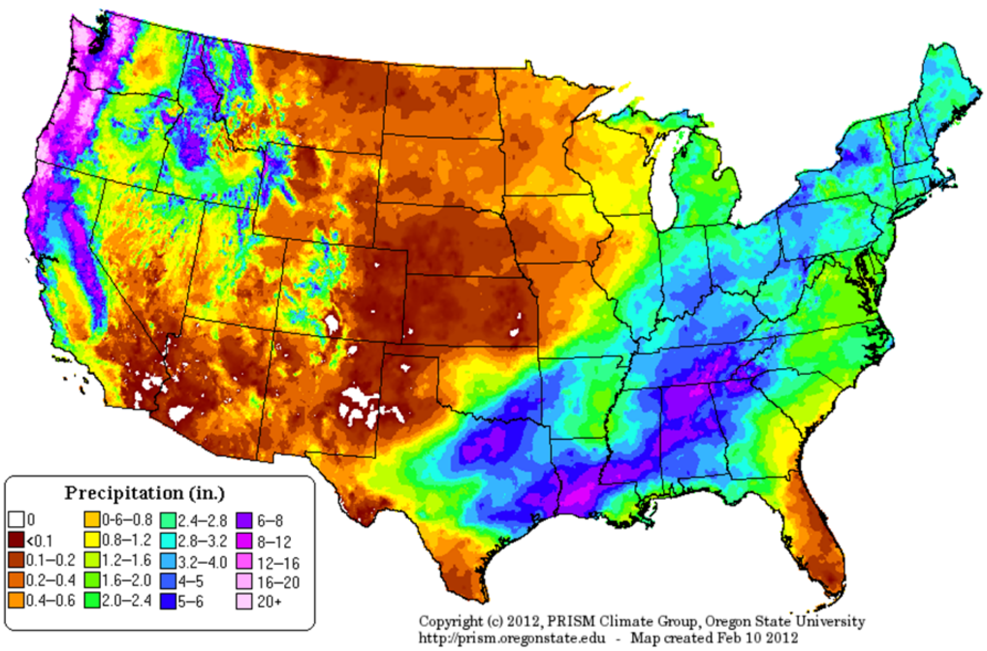

Figure 2.12: PRISM Precipitation Raster for the U.S in January 2012. (PRISM, 2012)

In the PRISM precipitation model (Daly et al. 1993), measured rainfall is corrected by elevation and aspect. Precipitation depth is decomposed, where the orographic part (affected by local topography) is estimated and differentiated from total depth.

A linear relationship between precipitation and elevation is assumed. Later, a regression function is fitted; this function estimates increment or decrement of precipitation for a new point in which the terrain elevation drops or raises. This precipitation differential corresponds to the orographic effect.

The PRISM precipitation model estimates rainfall from point measurements and terrain elevation. Its products are only available for the United States and its procedure could be duplicated in other parts of the world, taking into account the specific conditions. The precipitation and elevation function might vary significantly in different regions.

The distribution of precipitation could be integrated with streamflow and stream networks datasets. The resultant analysis could associate the spatial relation between precipitation and streamflow and how the water is transported and recorded; from precipitation to streamflow.

Chapter 3: Methodology

3.1 World Water Online Test Case: Mexico

In this chapter, a methodology for the compilation of Mexican water information is presented. At the end of the chapter, a Precipitation-Runoff analysis using the data in the system is performed. The application region is Hydrologic Region 28, containing the Papaloapan and Jamapa rivers in the state of Veracruz.

The integration of the Mexican HIS within WWO is made through the integration of the three CONAGUA networks: EMA's, EPPREPMEX and BANDAS (Figure 3.1). The first two systems can be considered dynamic systems, because data is being ingested continuously. The latter is considered a static system, due to the lack of automatic and continuous updates.

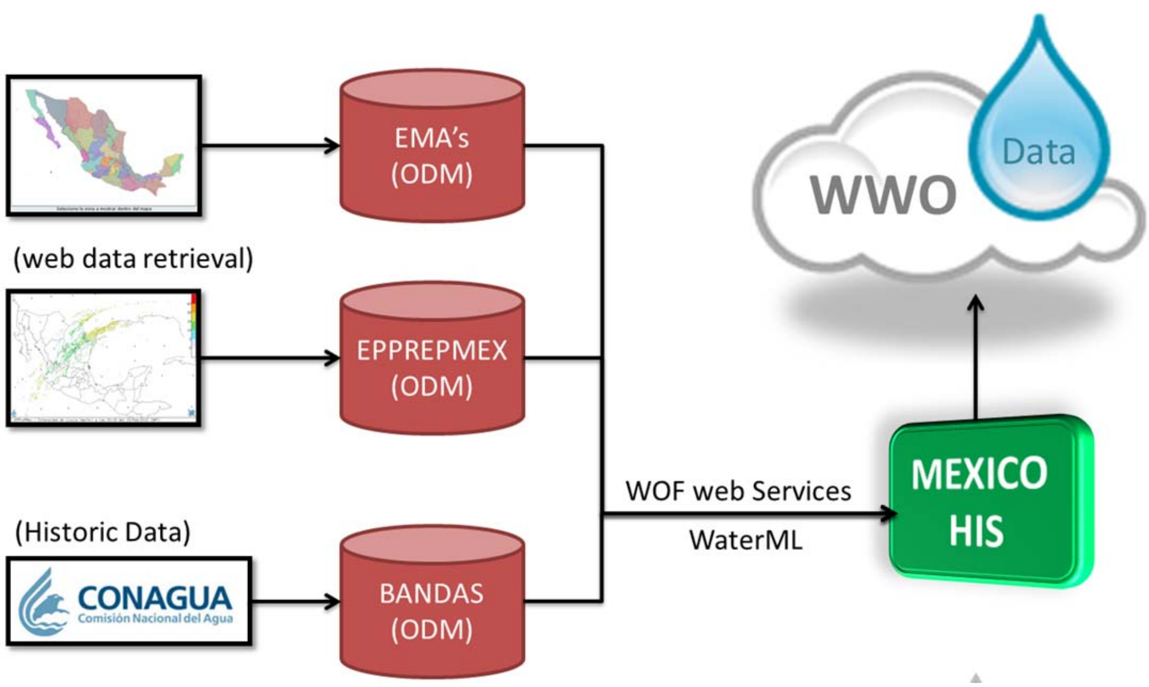

Figure 3.1: Mexican-HIS Scheme within World Water Online.

The EMA's and EPPREPMEX data is retrieved every day and stored in an ODM database. The BANDAS historic discharge data was migrated from dBASE and Microsoft Access formats to an ODM database. Data ingested for all values in the three systems is continuous, with a daily time interval, except only for the flood stage variable in EMA's, which is hourly.

CUAHSI-HIS schema is applied to Mexican-HIS. The ODM databases are published using WOF web services with WaterML as the interchange language. Physically, the ODM databases are stored on Center for Research in Water Resources (CRWR) servers.

3.1.1 Databases Access Codes

Database access codes are listed in Table 3.1. These web services can be used in CUAHSI clients (e.g. Hydroexcel or Hydrodesktop) but they are not registered and cannot be discovered using the CUAHSI-HIS central data catalog. Discovery of these web services is possible through the World Water Online group in ArcGIS Online. This scheme reinforces World Water Online as a top-level catalog: a catalog of catalogs in which global water data can be found.

Table 3.1: Web Services Links Strings for Data Access

System Database	Link String
EMA's Network	http://crwr-idis.austin.utexas.edu/CNASMNEA/cuahsi_1_0.asmx
EPPREPMEX system	http://crwr-idis.austin.utexas.edu/EPPREPMEX/cuahsi_1_0.asmx
BANDAS dataset	http://crwr-idis.austin.utexas.edu/BANDAS/cuahsi_1_0.asmx

3.1.2 Meteorological Data: EMA's Network

The Meteorological Network EMA's has 10 different variables for 493 stations throughout Mexico. The variables are listed in Table 3.2; the stations' locations are shown in Figure 3.2.

Table 3.2: EMA´s Network: Variables

Variable Code	Variable Name	Units	Time Support	Time Units
DIRR-24	Gust direction	degree	1	day
DIRS-24	Wind direction	degree	1	day
HR-24	Relative humidity	percent	1	day
PB-24	Barometric pressure	Hecto Pascal	1	day
PREC-24	Precipitation	millimeter	1	day
RAD-SOL-24	Radiation, total shortwave	watts per square meter	1	day
TEMP-24	Temperature	degree celsius	1	day
VELR-24	Gust speed	kilometers per hour	1	day
VELS-24	Wind speed	kilometers per hour	1	day
NIVEL-60	Water level*	meter	60	minute

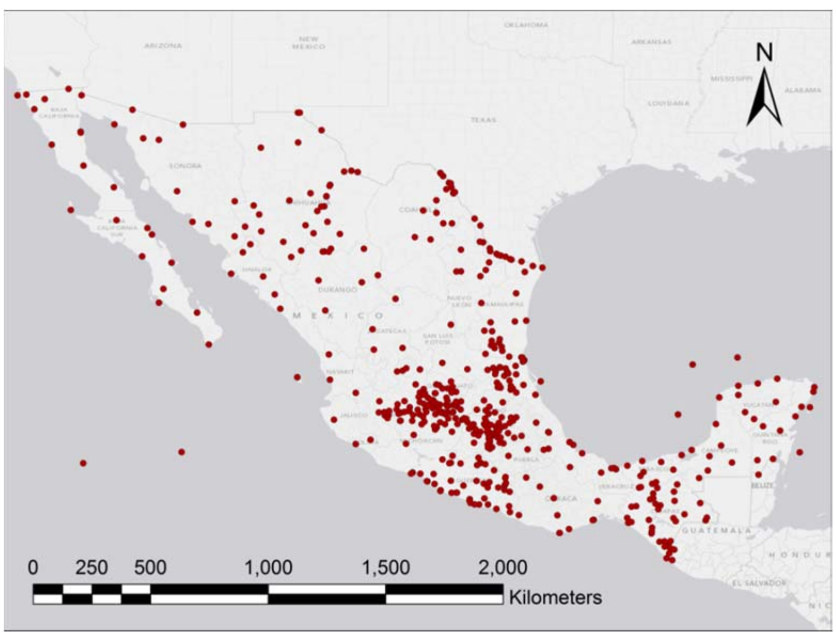

Figure 3.2: EMA's Network: Location of Stations.

A special variable within this system is water depth (flood stage). It has a different time interval (hourly instead of daily) and only 98 out of the 493 stations have this variable. This special case is discussed in the following section.

3.1.3 River Flood Stage: EMA's Network

The 98 stations with flood stage values in the EMA's network are located on five strategic rivers in Mexico: Lerma, Conchos, Bravo/Grande, Panuco and Grijalva. The stations and their hydrologic regions are shown in Figure 3.3.

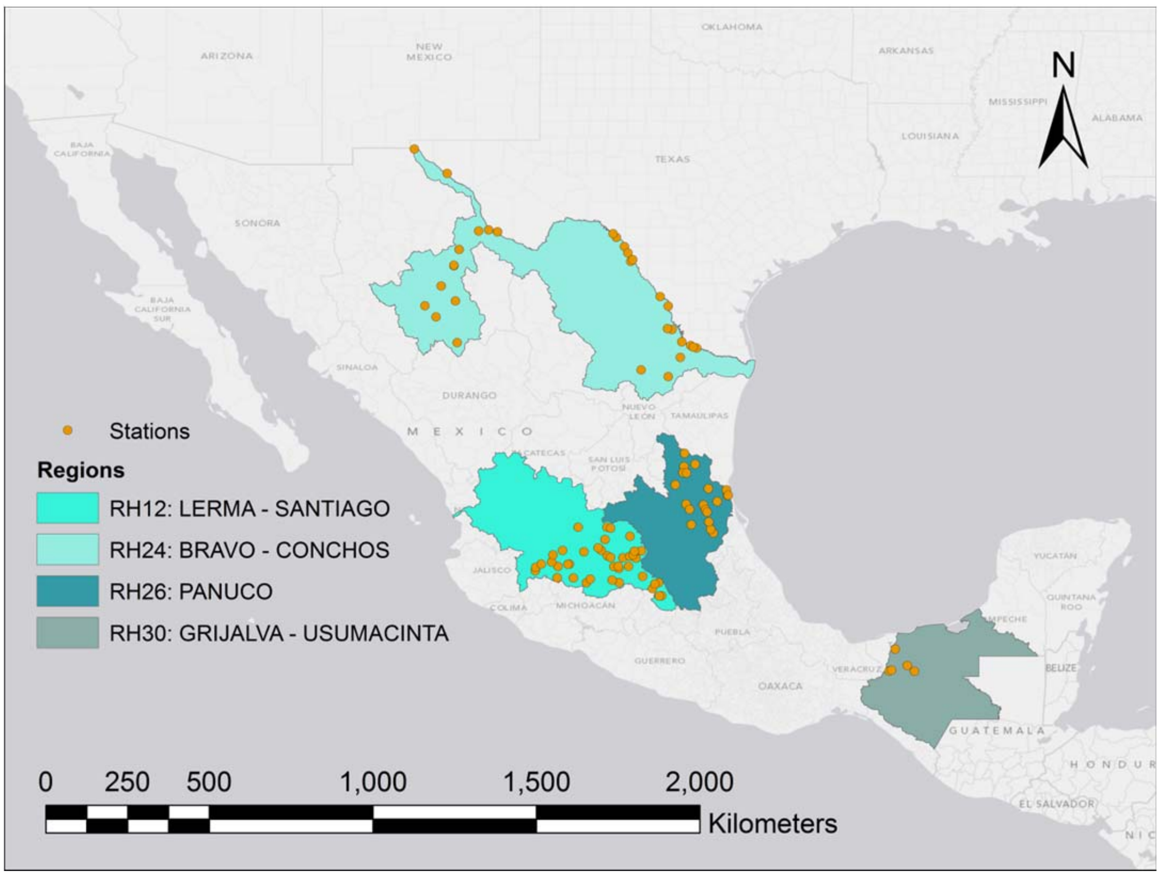

Figure 3.3: EMA's Network: Flood Stage Stations.

3.1.4 Derived Precipitation: EPPREPMEX System

The EPPREPMEX system has daily precipitation for 1,099 virtual stations. The variable code and information is shown in Table 3.3; the map of station locations is displayed in Figure 3.4.

Table 3.3: EPPREPMEX System: Variable Information

Variable Code	Variable Name	Units	Time Support	Time Units
PREC-24	Precipitation	millimeter	1	day

Figure 3.4: EPPREPMEX System: Virtual Stations.

3.1.5 Stream Discharge: BANDAS Dataset

The BANDAS dataset has stream discharge information for 2,249 gauging stations. An important part of this dataset is still not available at the time of writing (due to lack of information release, characteristics of the stations such as latitude and longitude, etc.). The integration of this dataset was done with a subset of 1,534 stations. These stations are located on main channels and have a longer time of record. The variable code and information is shown in Table 3.4; the station locations map is displayed in Figure 3.5.

Table 3.4: BANDAS System: Variable Information

Variable Code	Variable Name	Units	Time Support	Time Units
DD	Streamflow	cubic meters per second	1	day

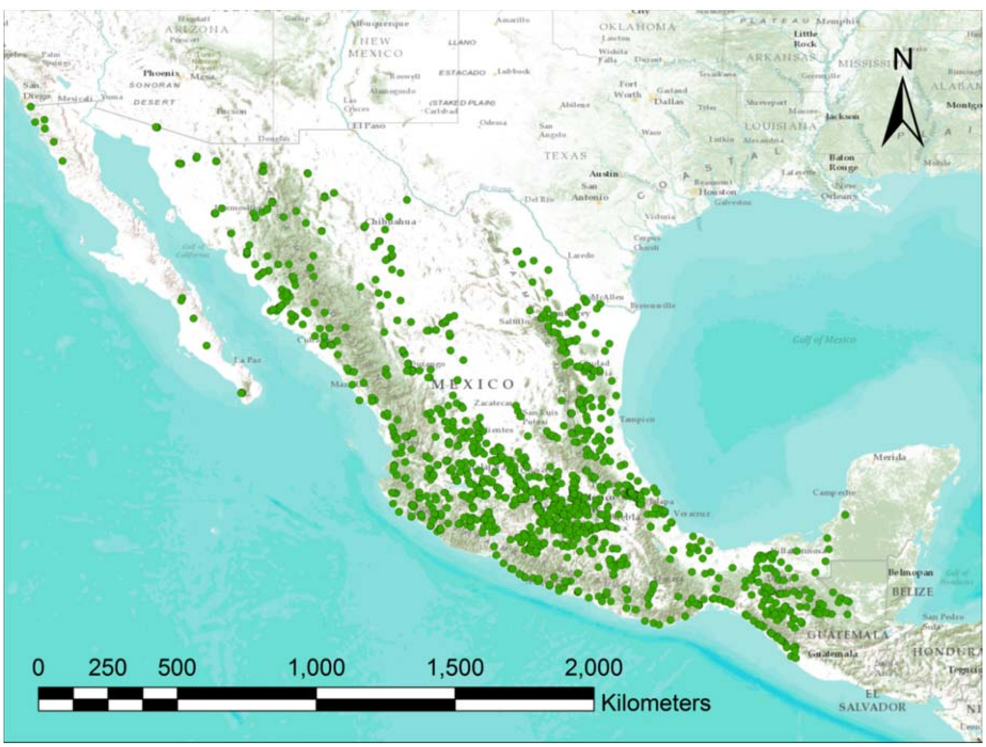

Figure 3.5: BANDAS Dataset: Discharge Gauging Stations.

3.2 PRECIPITATION-RUNOFF ANALYSIS

In the previous section, a methodology for integration of Mexican data in World Water Online was presented. Now data is available for use through web services and can be obtained in tabular format.

But World Water Online's mission goes beyond that point. It aims to produce and release more complex products and develop methodologies that could be reapplied for any part of the globe. One of the concerns of hydrologists is to know or predict the precipitation over an area and estimate mean stream discharge in the river network.

This chapter uses the Mexican-HIS data from World Water Online, and presents a methodology for creating a rainfall map for the country. Furthermore, a methodology for stream discharge estimation in rivers is presented in a study application case in hydrologic region 28.

For the temporal scope of this project, the application problem was narrowed by selecting twenty years of data for the analysis: a period of time from 1981 to 2000.

3.2.1 Hydrologic Region 28: Papaloapan River

Hydrologic region 28 is located in the east of Mexico. It includes part of the states of Veracruz, Oaxaca and Puebla. The predominant types of weather are sub-humid warm and humid warm. (INEGI, 2012)

The hydrologic region drains into the Gulf of Mexico throughout central Veracruz. Drainage starts from the mountainous range of *Sierra Oriental de Oaxaca* (a subdivision of the mountainous system *Sierra Madre del Sur*) in north Oaxaca, and the Trans-Mexican Volcanic Belt in east Puebla. (Figure 3.6)

Figure 3.6: Physiography of Hydrologic Region 28: Papaloapan River.

The hydrologic region is dived into two watersheds. In the south, one corresponds to the Papaloapan River itself (RH28A), which drains into Alvarado Lagoon (estuary); in the north, the other one (RH28B) encompasses the rivers Jamapa, Cotaxtla and Actopan. (Consejo de Cuenca del Rio Papaloapan, 2012 and Consejo de Cuenca de los Rios Tuxpan al Jamapa, 2012)

The population centers of Jalapa, Veracruz and Boca del Rio are located in RH28B. The cities of Orizaba and Cordoba are located in the northwest of RH28A, the latter one being on the hydrologic divide. The area is an economic center of the region and it is subject to flooding due to tropical storms in the Gulf of Mexico.

3.2.2 Process Diagram

The runoff analysis methodology (Figure 3.7) was separated into two main sections:

- Precipitation
- Streamflow.

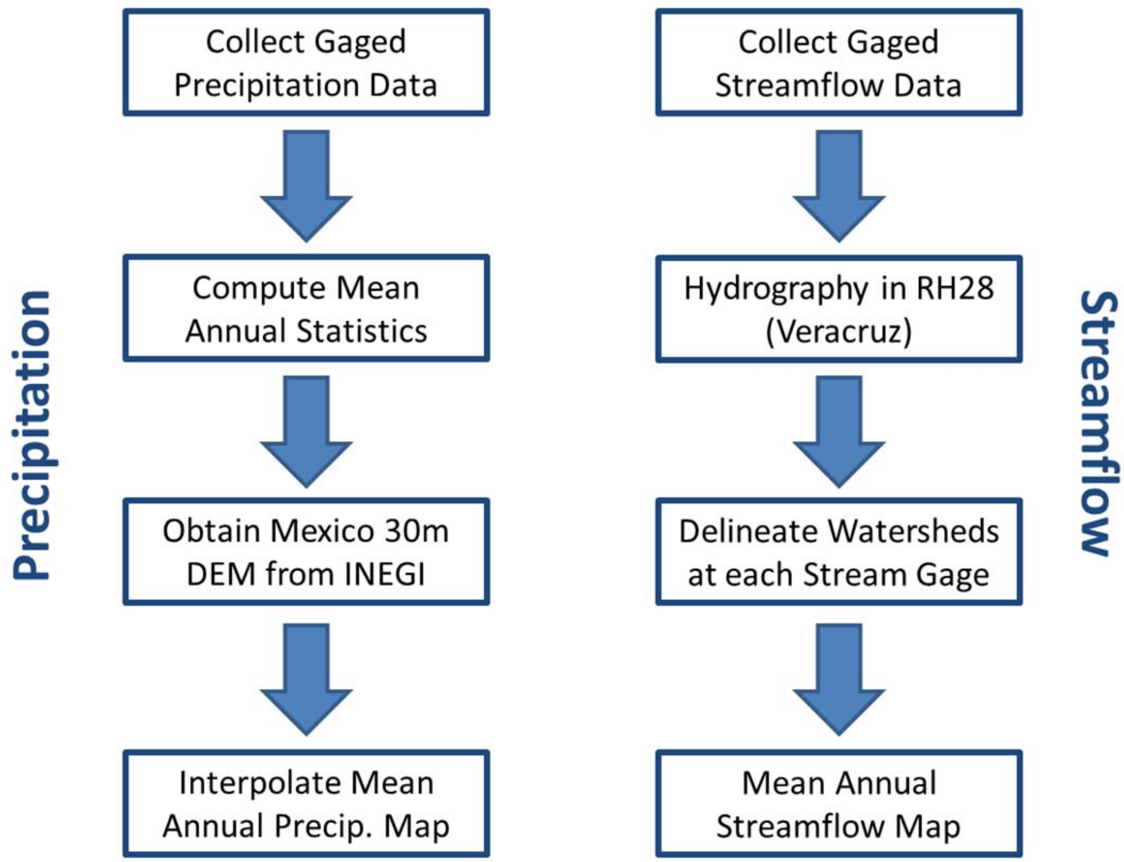

Figure 3.7: Precipitation-Runoff Analysis Flow Diagram.

Both sections begin with data gathering (Chapter 3.1). The precipitation part deals with spatial variations of rainfall and the orographic effects (Section 3.2.2.1).

The streamflow part deals with terrain processing (Section 3.2.2.2); it focuses on topography and how the water flows through the surface. The analysis is followed by creating Precipitation-Runoff relationships (Section 3.2.2.3) that quantitatively describe runoff for a given precipitation and its spatial distribution. Finally, the last part presents the extracted stream network (Section 3.2.2.4) and the appended mean annual runoff value for each stream link.

3.2.2.1 Precipitation Analysis

Due to its relevance in a national context, the precipitation analysis was made for the entire country, not only for the study area. The methodology presented in this chapter could be applied for a different area of the globe, using a DEM, precipitation and discharge stations.

Seventy-three stations from EMA's network provided mean precipitation data for the selected period, an average of 32,000 square kilometers per station. The list of stations and their mean precipitation values are listed in the Appendix.

Before being geographically interpolated, the precipitation was corrected by altitude (Daly et al. 1993). Each precipitation value was decomposed into two parts, considering the measured precipitation as the addition of estimated precipitation at sea level and an orographic increment (or decrement).

The geographic interpolation is performed at sea level, using the Kriging technique. Afterwards, the orographic component is added. It varies spatially, taking into account local topography and weather.

The orographic component of precipitation was taken as a function of terrain elevation. This function was assumed to be the same for equal conditions of climate and weather.

Due to the different types of weather across Mexico, the country was separated into six hydrologic units. These units are a collection of regions. It is assumed that a single precipitation-elevation function characterizes each hydrologic unit, and each function is independent from one region to another. These hydrologic units were created from basin divisions of INEGI's Hydrography Network 2.0. Each hydrologic unit was a result of merging contiguous hydrologic regions. The hydrologic units and their included hydrologic regions are listed in the Table 3.5 and shown in Figure 3.8.

Table 3.5: Hydrologic Units in Mexico

Hydrologic Unit	**Hydrologic Regions Included**
I	03, 05, 06, 08, 09
II	10, 24, 34
III	11, 12, 15, 16, 36, 37
IV	25, 26, 27
V	18, 19, 20, 21, 23, 28, 29, 30
VI	31, 32, 33

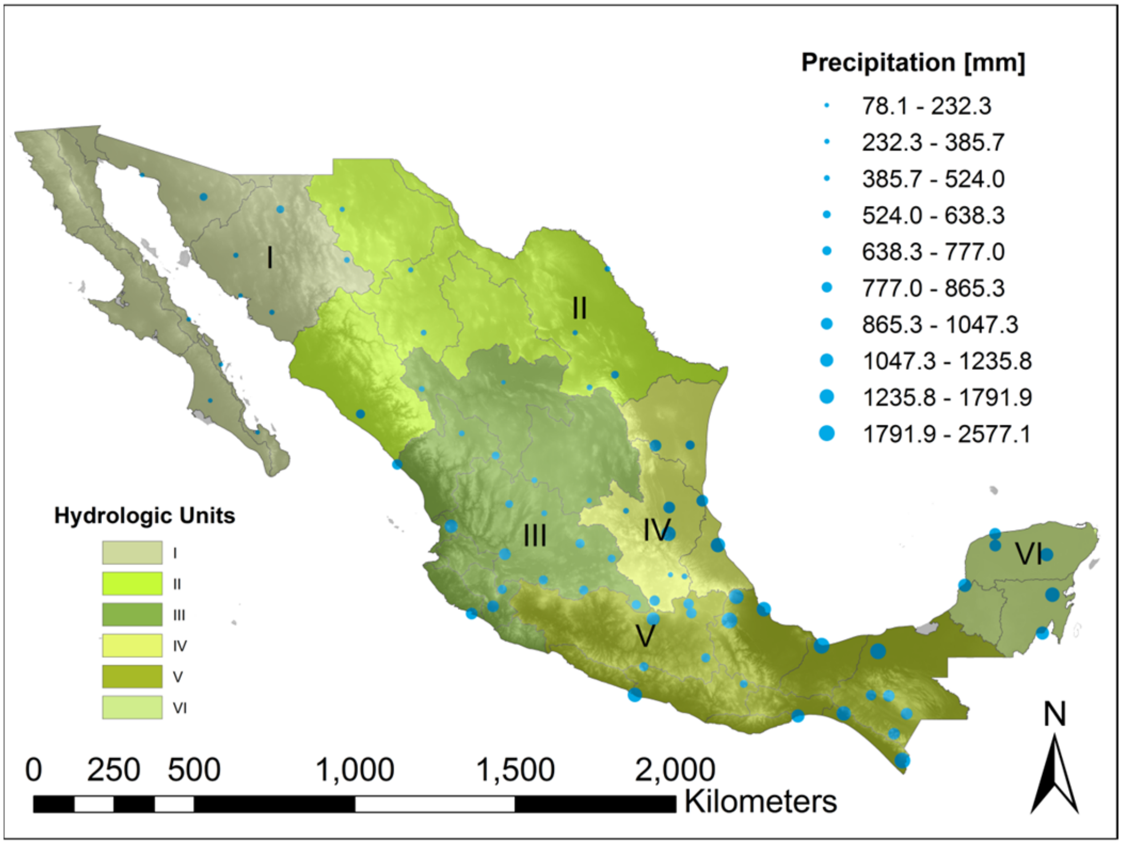

Figure 3.8: Hydrologic Units and Mean Precipitation for EMA's Network 1981 - 2000.

For each hydrologic unit a linear function was assumed: ($P = m\ E + b$) where m and b are fitting parameters, P is the precipitation in millimeters and E is the terrain elevation above sea level in meters (masl).

The increment in precipitation was calculated with the equation $\Delta P = m\ \Delta E$. The datum (zero elevation) was referenced by mean sea level. For the purpose of this project, different from PRISM, the precipitation was not corrected by the geographic orientation of the dominant slope (aspect). The value of the m parameter was set at the precipitation stations' locations and interpolated geographically in order to smooth the transition between hydrologic units.

All the stations used are below 2,500 masl, which creates uncertainty in the points above this elevation. The recommendation (Daly et al. 1993) of limiting the maximum precipitation increment ΔP was applied. The precipitation increment ΔP was set constant for elevation points higher than 3,000 masl. Regression plots and statistics for all hydrologic units are shown in Figure 3.9 and Table 3.6.

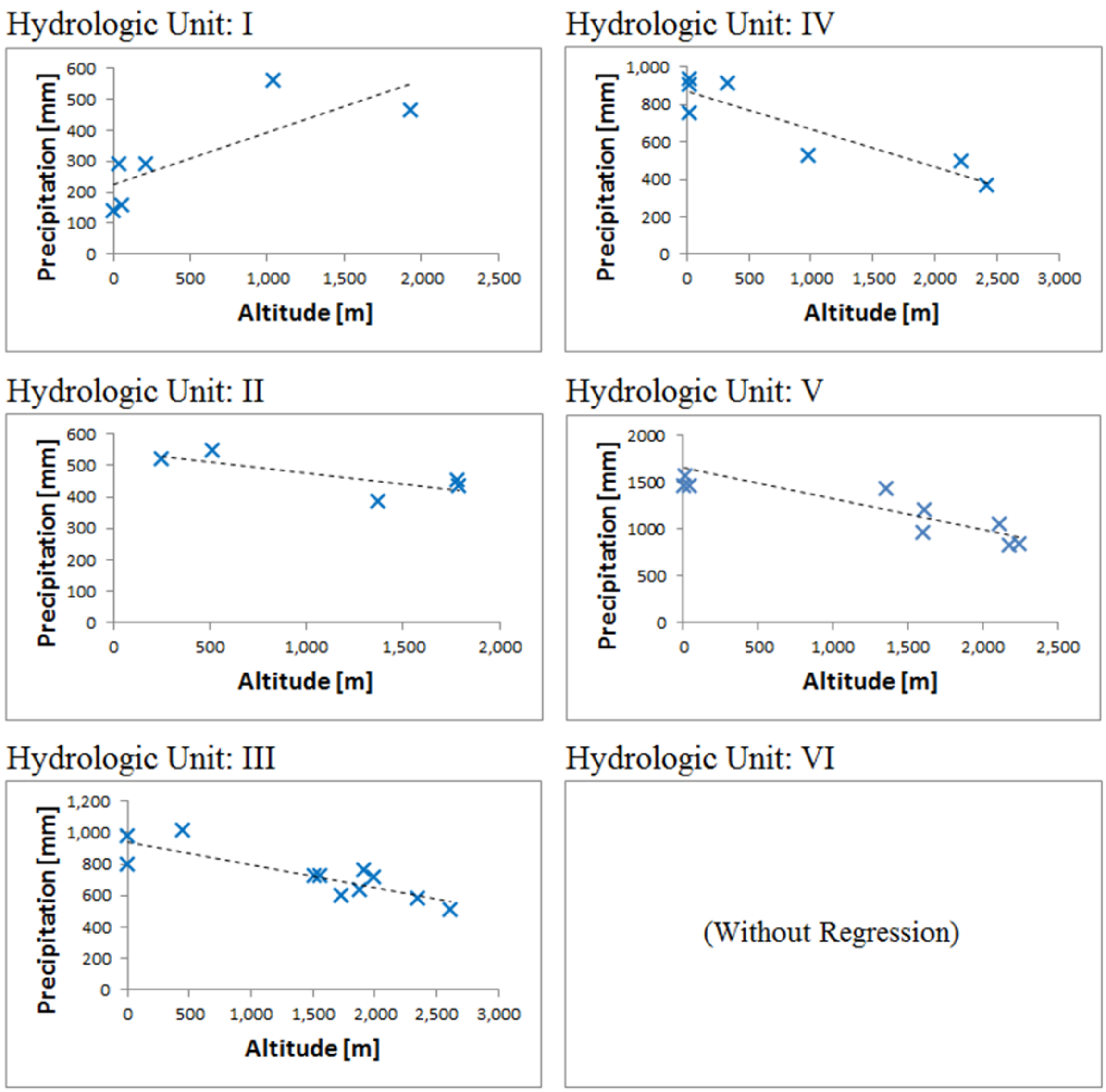

Figure 3.9: Precipitation–Runoff Regressions (EMA's).

Table 3.6: Statistical Parameters for the Precipitation-Elevation Plots (EMA's).

Hydrologic Unit	m (t statistic)	b (t statistic)	R^2	Standard Error	F statistic	Significance F
I	0.1702 (2.6859)	223.38 (3.9143)	0.6433	110.89	7.21	0.0549
II	-0.0715 (-2.2211)	548.44 (12.9931)	0.6219	46.37	4.93	0.1129
III	-0.1486 (-4.9914)	945.85 (18.7784)	0.7346	85.04	24.91	0.0007
IV	-0.2037 (-4.8520)	873.58 (15.9810)	0.8248	108.47	23.54	0.0047
V	-0.2685 (-5.1164)	1532.10 (18.9619)	0.7249	142.73	26.18	0.0014
VI	-----	-----	-----	-----	-----	-----

The Yucatan Peninsula (hydrologic unit VI) is a low elevation, flat geographic area. Due to the small correlation between precipitation and elevation across the hydrologic unit, there was no correction in precipitation due to elevation. The orographic component was taken as equal to zero.

Moreover, the verification or modification of the previous regression plots was done with the data in the EPPREPMEX system. The 1,099 stations provide the cumulative precipitation for the period of time between August '11 and January '12. Regression plots and statistics for all hydrologic units are shown in Figure 3.10 and Table 3.7.

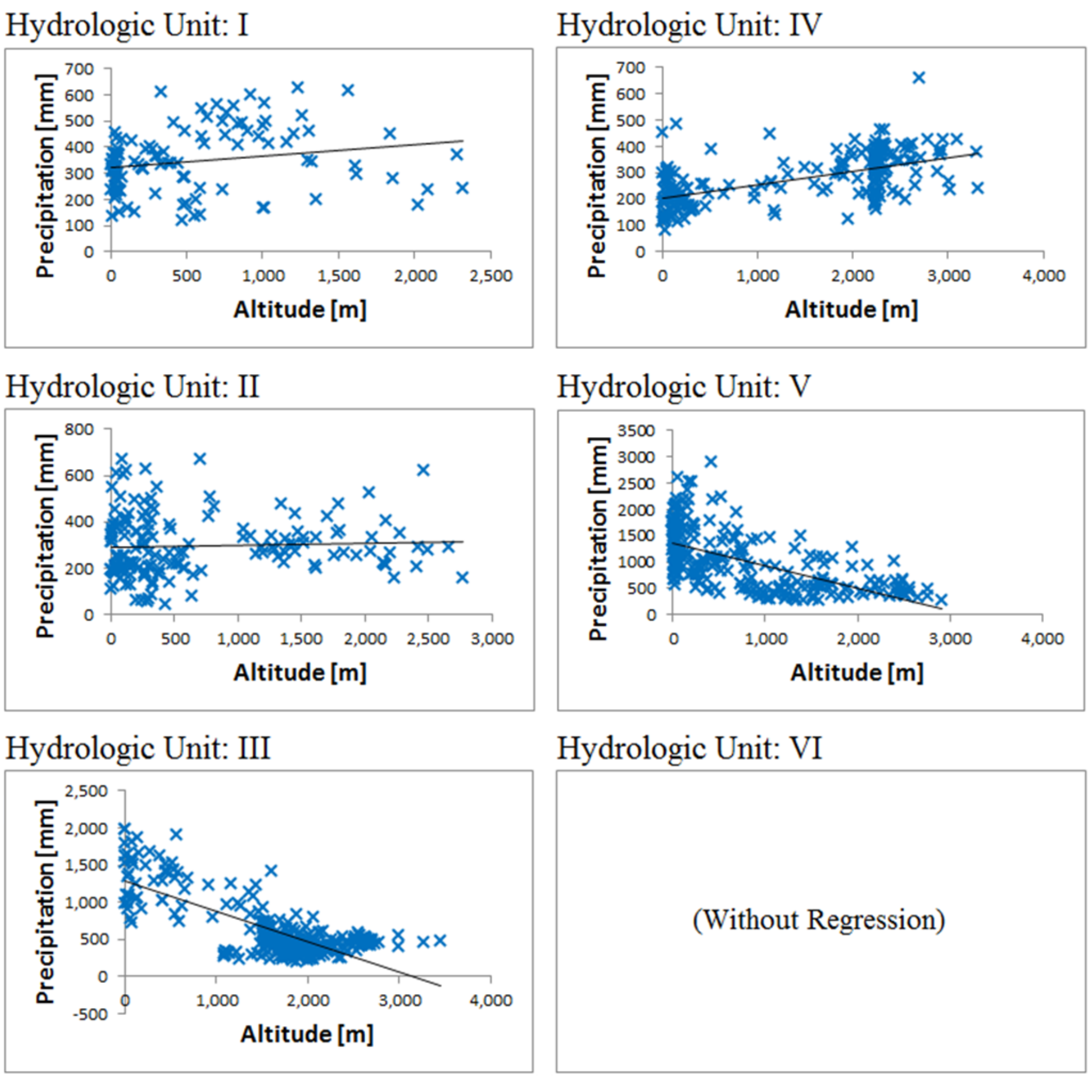

Figure 3.10: Precipitation–Runoff Regressions (EPPREPMEX).

Depending on the local topographic conditions, the precipitation may increase or decrease with elevation. The precipitation tends to decrease with altitude in mountainous areas with relative low precipitation (Daly et al. 1993) such as Arizona, Nevada and Idaho in the United States. While in sub-humid and tropical regions, the maximum precipitation occurs below mountains' peaks, such as Hawai, and the precipitation decreases with elevation.

Table 3.7: Statistical Parameters for the Precipitation-Elevation Plots (EPPREPMEX).

Hydrologic Unit	m (t statistic)	b (t statistic)	R^2	Standard Error	F statistic	Significance F
I	0.0439 (2.1975)	322.47 (20.4627)	0.0436	118.56	4.83	0.0302
II	0.0101 (0.7367)	288.19 (21.0531)	0.0033	130.28	0.54	0.4624
III	-0.4083 (-20.2840)	1281.8 (35.1674)	0.5759	248.33	411.44	0.0000
IV	0.0510 (9.8568)	203.97 (21.5248)	0.3270	76.10	97.16	0.0000
V	-0.4247 (-12.7545)	1361.00 (35.5339)	0.3895	437.66	162.68	0.0000
VI	-----	-----	-----	-----	-----	-----

The significance F values for the hydrologic units I and II in Table 3.6 shows that there is not enough correlation between variables. The plot for hydrologic unit IV in the EPPREPMEX shows an uphill gradient instead of the downhill gradient in EMA's. Comparing the statistics, the data from EMA's in this specific case is not enough to get reliable results, the EPPREPMEX regression is used in this case.

3.2.2.2 Terrain Processing

In the terrain processing section, DEM data and discharge stations' locations were the inputs. The DEM was reconditioned for use in water resources: the pits were filled, the flow direction of each cell was determined and flow accumulation was performed. These steps were run using the tools in ArcGIS. With the information generated (flow direction), the drainage area of each discharge station was delineated.

Seventeen stations located within hydrologic region 28 were selected. These stations include a complete record for the time period of analysis (1981 - 2000). Discharge data for each station is shown in Table 3.8. The reconditioned DEM, location of discharge stations and their drainage areas are shown in Figure 3.11

Table 3.8: Mean Annual Discharge for Stations in Hydrologic Region 28.

Station Number	Station Name	Water Object Name	Discharge [m^3/s]
28001	San Juan Evangelista	Rio San Juan	204.58
28003	Cardel	Rio La Antigua	56.02
28014	Papaloapan	Rio Papaloapan	568.12
28015	Cuatotolapan	Rio San Juan	236.15
28025	Lauchapan	Rio Chicalopa	46.85
28030	Actopan II	Rio Actopan	18.30
28039	Paso Del Toro	Rio Cotaxtla	40.96
28040	El Tejar	Rio Jamapa	18.62
28069	Capulines	Rio Cotaxtla	58.63
28108	El Naranjillo	Rio Actopan	15.59
28111	Idolos	Rio Idolos	5.04
28125	Carrizal	Rio La Antigua	46.65
28133	Amatitla II	Rio Pescados	22.27
28134	Jalcomulco	Rio La Antigua	47.10
28136	Garro	Rio Tesechoacan	168.09
28153	La Ceibilla	Rio San Juan	251.49
28188	El Zetal	Rio Actopan	1.03

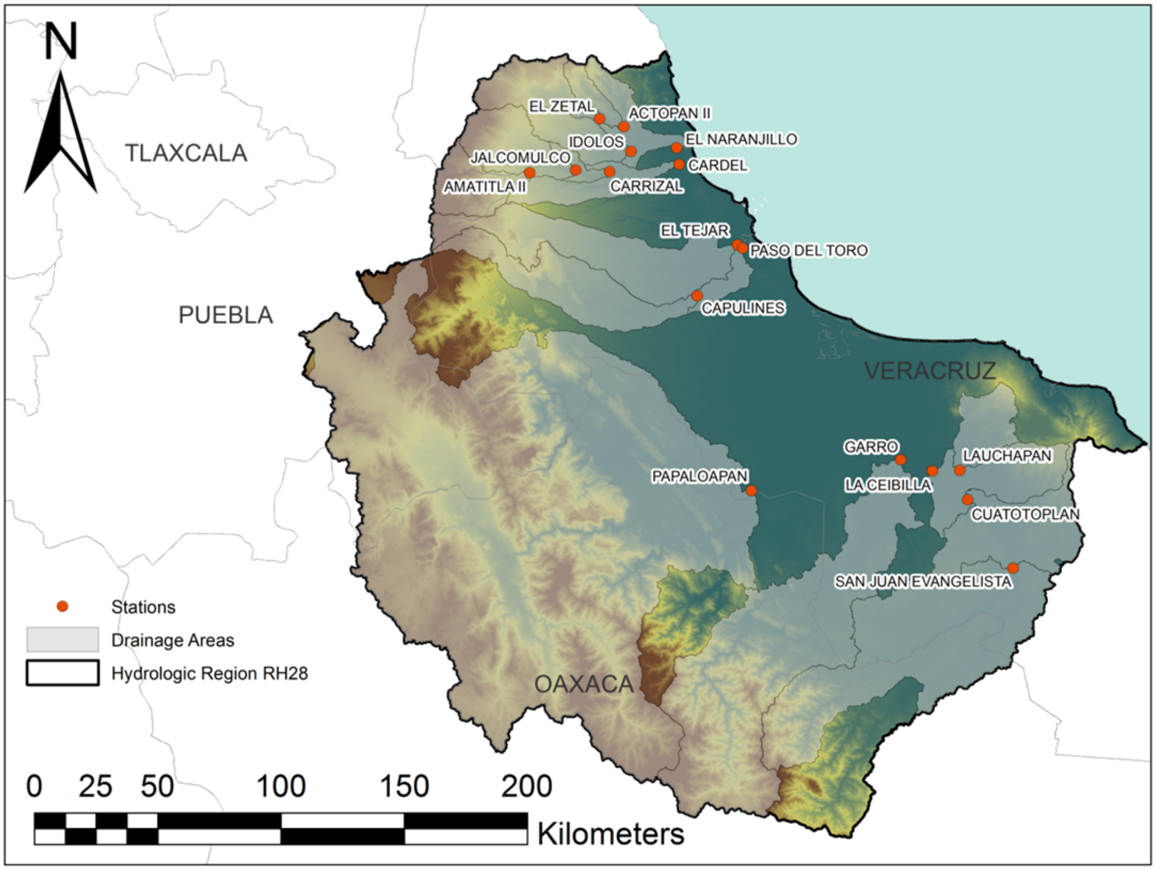

Figure 3.11: Discharge Stations and Drainage Area within Hydrologic Region 28.

3.2.2.3 Precipitation- Runoff Relationship

The precipitation-runoff analysis was created for a yearly time interval. The mean precipitation over each station's drainage area was computed from the precipitation raster. Discharge data (cubic meters per second) for each station was expressed per unit area (millimeters/year). The previous values were plotted and correlated fitting a function $Q = mP^n$, where Q is discharge, P precipitation. The regression plot and the statistical parameters are shown in Figure 3.12 and Table 3.9.

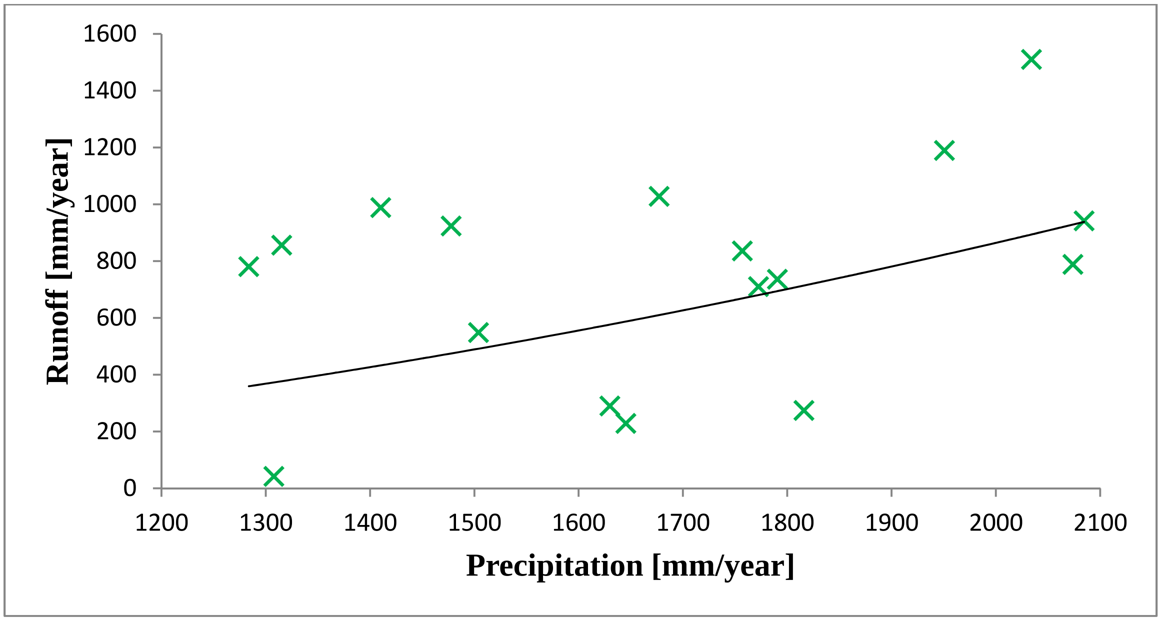

Figure 3.12: Precipitation-Runoff Regression for Hydrologic Region 28.

Table 3.9: Statistical Parameters for Precipitation-Runoff Regression.

n (t statistic)	m (t statistic)	R^2	Standard Error	F statistic	Significance F
1.9798 (1.5476)	0.000252 (-0.8734)	0.1377	245.59	2.39	0.1426

The equation $Q = 0.000252P^{1.9798}$ was the transformation function between precipitation and discharge for all the points in the basin.

3.2.2.4 Stream Network

In the previous section, we had obtained a precipitation-discharge function. This expression was used for computing the discharge per unit area raster (Figure 3.13) from the precipitation raster.

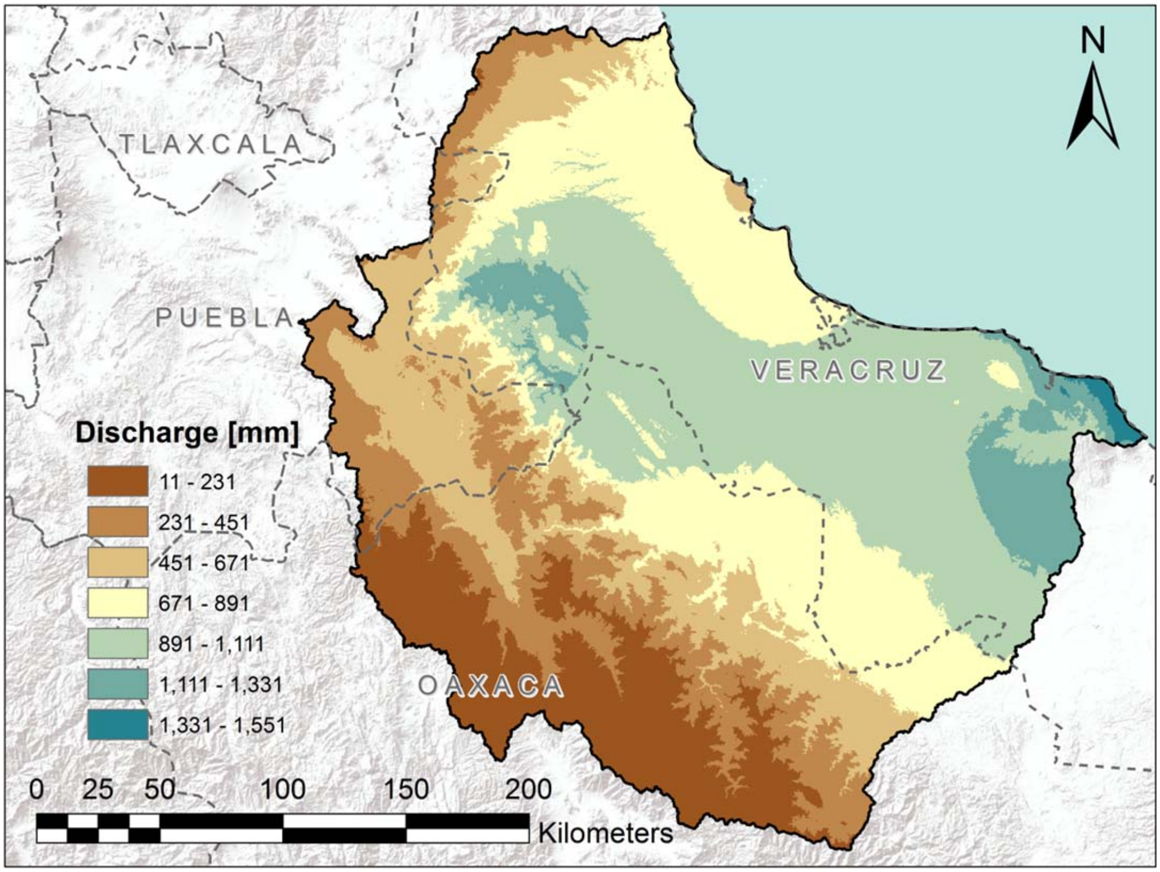

Figure 3.13: Mean Annual Discharge per Unit Area for Hydrologic Region 28.

The values show the spatial variation of discharge across the hydrologic region. The discharge per unit area represents the water depth of precipitation that flows through the terrain and reaches the streams. The ratio of discharge to precipitation is shown in Figure 3.14.

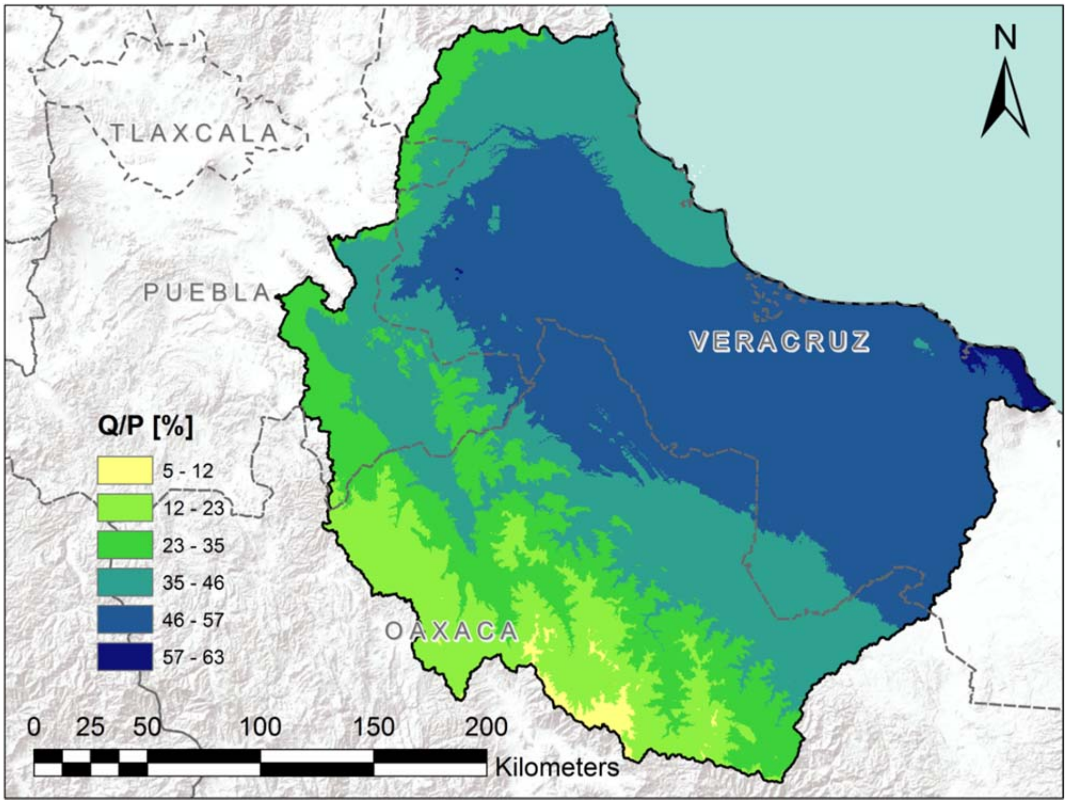

Figure 3.14: Discharge/Precipitation Ratio for Hydrologic Region 28.

The estimated runoff for each cell is computed with the flow accumulation, using discharge raster values as weights. That is equivalent to the following expression:

$$R = n \times Q \times d^2 / C$$

where:

- n is the number of cells upstream [cells]
- R is the runoff [cubic meters per second]
- Q is the discharge per unit area [millimeters per year]
- d is the cell size of the discharge raster, equal to 31.74 [meters]
- C is a constant factor that transforms temporal and longitudinal units equal to $\left(\frac{1{,}000mm}{1m}\right)\left(\frac{365d}{1yr}\right)\left(\frac{86{,}400s}{1d}\right) = 31.536 \times 10^9$

The stream network (Figure 3.15) was extracted from the runoff raster, given a threshold value of 0.1 cubic meters per second. Each river reach contains a mean annual runoff value for that particular stream. The network was created with all the tracing capabilities, in which all the elements are connected and the flow directions were determined with sinks located along the Gulf of Mexico coast.

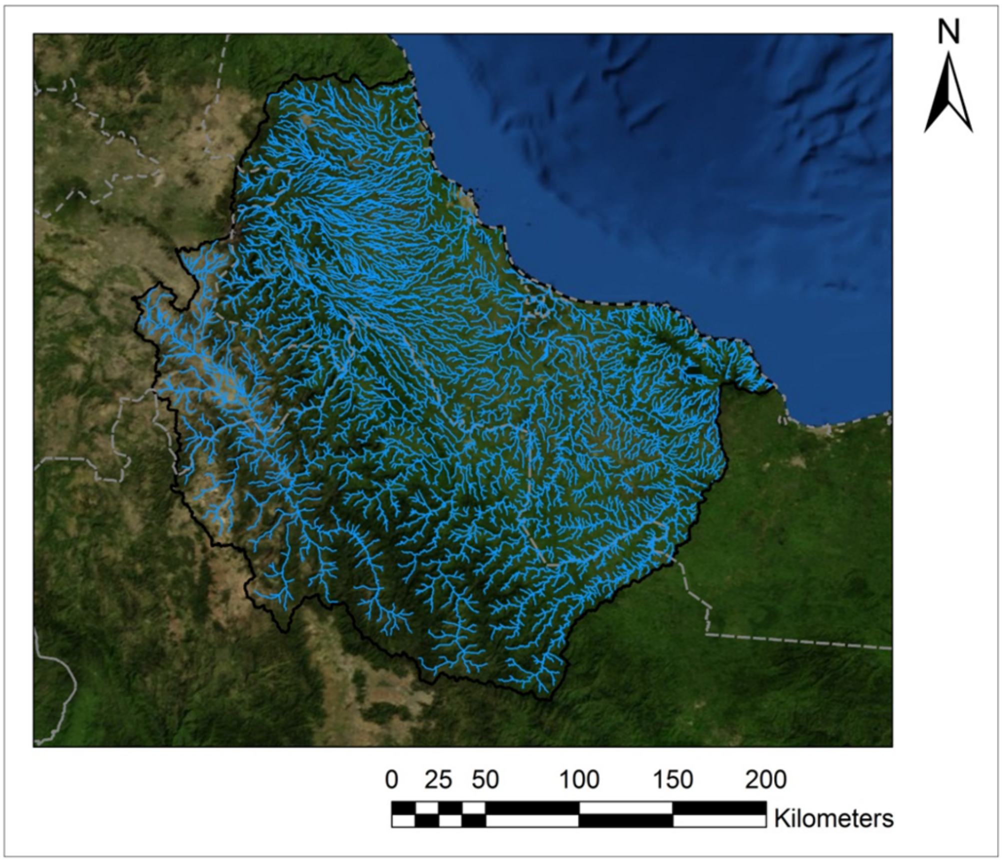

Figure 3.15: Stream Network Extracted from Discharge Raster for Hydrologic Region 28.

The streams are an interconnected network. For any given point in a river reach, the outlet can be tracked downstream until it reaches the ocean. It also can be tracked upstream to find the river reaches of influence at that particular point.

Chapter 4: Results

4.1 Data Access through Web Services

The ODM databases were created and published using WaterOneFlow (WOF) web services. The string codes for each database are presented in Table 4.1.

Table 4.1: Web Services Link Strings for Data Access

System Database	String Code	Web Service URL
EMA's Network	CNASMNEA	http://crwr-idis.austin.utexas.edu/CNASMNEA/
EPPREPMEX system	EPPREPMEX	http://crwr-idis.austin.utexas.edu/EPPREPMEX/
BANDAS dataset	BANDAS	http://crwr-idis.austin.utexas.edu/BANDAS/

4.1.1 GetSites Method

The GetSites method can be used to get all sites or to get a subset of sites. For the first case, the method is accessed with only the system database string code (green) as a parameter. For the latter case, the method is accessed with the system database string code (green) and the desired site code(s) (blue) as parameters. The GetSites method string for all the sites is shown in Figure 4.1 and for a subset of sites is shown in Figure 4.2. The example response is shown in Figure 4.3.

http://crwr-idis.austin.utexas.edu/EPPREPMEX/cuahsi_1_1.asmx/GetSitesObject?

site=&authToken=

Figure 4.1: Example String of GetSites Method (All Sites).

http://crwr-idis.austin.utexas.edu/EPPREPMEX/cuahsi_1_1.asmx/GetSitesObject?

site=EPPREPMEX:AGS-1&

site=EPPREPMEX:AGS-5&

site=EPPREPMEX:AGS-8&

authToken=

Figure 4.2: Example String of GetSites Method (Subset).

```
− <sitesResponse>
  − <queryInfo>
      <creationTime>2012-03-20T15:25:57.4709852-05:00</creationTime>
    − <criteria MethodCalled="GetSites">
        <parameter name="site" value="EPPREPMEX:AGS-1"/>
        <parameter name="site" value="EPPREPMEX:AGS-5"/>
        <parameter name="site" value="EPPREPMEX:AGS-8"/>
      </criteria>
    </queryInfo>
  − <site>
    − <siteInfo>
        <siteName>Aguasc. Of.</siteName>
        <siteCode network="EPPREPMEX" siteID="1">AGS-1</siteCode>
      − <geoLocation>
        − <geogLocation xsi:type="LatLonPointType">
            <latitude>21.883</latitude>
            <longitude>-102.3</longitude>
          </geogLocation>
        </geoLocation>
      </siteInfo>
    </site>
  − <site>
    − <siteInfo>
        <siteName>P.Calles</siteName>
        <siteCode network="EPPREPMEX" siteID="7">AGS-5</siteCode>
      − <geoLocation>
        − <geogLocation xsi:type="LatLonPointType">
            <latitude>22.133</latitude>
            <longitude>-102.433</longitude>
          </geogLocation>
        </geoLocation>
      </siteInfo>
    </site>
  − <site>
    − <siteInfo>
        <siteName>P.Potrerillo</siteName>
        <siteCode network="EPPREPMEX" siteID="10">AGS-8</siteCode>
      − <geoLocation>
        − <geogLocation xsi:type="LatLonPointType">
            <latitude>22.233</latitude>
            <longitude>-102.433</longitude>
          </geogLocation>
        </geoLocation>
      </siteInfo>
    </site>
  </sitesResponse>
```


Figure 4.3: Example Response from GetSites Method.

4.1.2 GetSiteInfo Method

An example of the GetSiteInfo method is presented in Figure 4.4. The method is accessed with the system database string code (green) and the site code (blue) as parameters. The example response is shown in Figure 4.5.

```
http://crwr-idis.austin.utexas.edu/CNASMNEA/cuahsi_1_1.asmx/GetSiteInfoObject?
                                        site=CNASMNEA:HI08&
                                        authToken=
```

Figure 4.4: Example String of GetSiteInfo Method.


```
- <sitesResponse>
  - <queryInfo>
      <creationTime>2012-03-20T14:49:46.9935474-05:00</creationTime>
    - <criteria MethodCalled="GetSiteInfo">
        <parameter name="site" value="CNASMNEA:HI08"/>
      </criteria>
    </queryInfo>
  - <site>
    - <siteInfo>
        <siteName>TAXHIMAY; HGO.</siteName>
        <siteCode network="CNASMNEA" siteID="245">HI08</siteCode>
      - <geoLocation>
        - <geogLocation xsi:type="LatLonPointType">
            <latitude>19.837222</latitude>
            <longitude>-99.383888</longitude>
          </geogLocation>
        </geoLocation>
        <elevation_m>2256</elevation_m>
        <verticalDatum>MSL</verticalDatum>
      </siteInfo>
    + <seriesCatalog menuGroupName="[YOUR DATASET] Observations" serviceWsdl="http://crwr-
      idis.austin.utexas.edu/CNASMNEA/cuahsi_1_1.asmx?WSDL"></seriesCatalog>
    </site>
  </sitesResponse>
```


Figure 4.5: Example Response from GetSiteInfo Method.

4.1.3 GetVariableInfo Method

The access string of the GetVariableInfo method is shown in Figure 4.6. The method is accessed with the system database string code (green) and the variable code (blue) as parameters. The example response is shown in Figure 4.7.

```
http://crwr-idis.austin.utexas.edu/ CNASMNEA/cuahsi_1_1.asmx/GetVariableInfoObject?
                                        variable=CNASMNEA:PREC-24&
                                        authToken=
```

Figure 4.6: Example String of GetVariableInfo Method.


```
- <variablesResponse>
  - <queryInfo>
      <creationTime>2012-03-20T14:52:50.9982578-05:00</creationTime>
    - <criteria MethodCalled="GetVariableInfo">
        <variableParam>CNASMNEA:PREC-24</variableParam>
        <parameter name="variable" value="CNASMNEA:PREC-24"/>
      </criteria>
      <note>OD Web Service</note>
    </queryInfo>
  - <variables>
    - <variable>
        <variableCode vocabulary="CNASMNEA" default="true" variableID="14">PREC-24</variableCode>
        <variableName>Precipitation</variableName>
        <valueType>Field Observation</valueType>
        <dataType>Incremental</dataType>
        <generalCategory>Climate</generalCategory>
        <sampleMedium>Precipitation</sampleMedium>
      - <unit>
          <unitName>millimeter</unitName>
          <unitType>Length</unitType>
          <unitAbbreviation>mm</unitAbbreviation>
          <unitCode>54</unitCode>
        </unit>
        <noDataValue>-9999</noDataValue>
      - <timeScale isRegular="true">
        - <unit>
            <unitName>day</unitName>
            <unitType>Time</unitType>
            <unitAbbreviation>d</unitAbbreviation>
            <unitCode>104</unitCode>
          </unit>
          <timeSupport>1</timeSupport>
        </timeScale>
        <speciation>Not Applicable</speciation>
      </variable>
    </variables>
  </variablesResponse>
```


Figure 4.7: Example Response from GetVariableInfo Method.

4.1.4 GetValues Method

The GetValues method accesses the recorded values in the system. The method is used with the system database string code (green), the site code (blue), the variable code (orange) and the start and end dates (red) as parameters.

The date strings could be left blank; for this case the system will return all time series for the given site and variable. An example of GetValues access string is shown in Figure 4.8. The example response is shown in Figure 4.9.

```
http://crwr-idis.austin.utexas.edu/CNASMNEA/cuahsi_1_1.asmx/GetValuesObject?
    location=CNASMNEA:VR15&
    variable=CNASMNEA:NIVEL-60&
    StartDate=2011-10-21&
    EndDate=2011-10-22&
    authToken=
```

Figure 4.8: Example String of GetValues Method.

```
− <timeSeriesResponse>
  − <queryInfo>
      <creationTime>2012-03-20T16:18:13.7420832-05:00</creationTime>
    − <criteria MethodCalled="GetValues">
        <parameter name="site" value="CNASMNEA:VR15"/>
        <parameter name="variable" value="CNASMNEA:NIVEL-60"/>
        <parameter name="startDate" value="2011-10-21"/>
        <parameter name="endDate" value="2011-10-22"/>
      </criteria>
    </queryInfo>
  − <timeSeries>
    − <sourceInfo xsi:type="SiteInfoType">
        <siteName>PANUCO; VER</siteName>
        <siteCode network="CNASMNEA" siteID="470">VR15</siteCode>
      + <geoLocation></geoLocation>
        <elevation_m>2</elevation_m>
        <verticalDatum>MSL</verticalDatum>
      </sourceInfo>
    + <variable></variable>
    − <values>
        <value censorCode="nc" dateTime="2011-10-21T00:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T06:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.53</value>
        <value censorCode="nc" dateTime="2011-10-21T01:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T07:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.56</value>
        <value censorCode="nc" dateTime="2011-10-21T02:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T08:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.58</value>
        <value censorCode="nc" dateTime="2011-10-21T03:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T09:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.59</value>
        <value censorCode="nc" dateTime="2011-10-21T04:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T10:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.59</value>
        <value censorCode="nc" dateTime="2011-10-21T05:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T11:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.58</value>
        <value censorCode="nc" dateTime="2011-10-21T06:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T12:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.57</value>
        <value censorCode="nc" dateTime="2011-10-21T07:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T13:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.54</value>
        <value censorCode="nc" dateTime="2011-10-21T08:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T14:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.53</value>
        <value censorCode="nc" dateTime="2011-10-21T09:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T15:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.52</value>
        <value censorCode="nc" dateTime="2011-10-21T10:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T16:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.5</value>
        <value censorCode="nc" dateTime="2011-10-21T11:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T17:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.47</value>
        <value censorCode="nc" dateTime="2011-10-21T12:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T18:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.47</value>
        <value censorCode="nc" dateTime="2011-10-21T13:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T19:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.47</value>
        <value censorCode="nc" dateTime="2011-10-21T14:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T20:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.46</value>
        <value censorCode="nc" dateTime="2011-10-21T15:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T21:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.44</value>
        <value censorCode="nc" dateTime="2011-10-21T16:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T22:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.41</value>
        <value censorCode="nc" dateTime="2011-10-21T17:00:00" timeOffset="-06:00" dateTimeUTC="2011-10-21T23:00:00" methodCode="1"
        sourceCode="4" qualityControlLevelCode="-9999">0.39</value>
```


Figure 4.9: Example Response from GetValues Method.

4.2 ArcGis Online: World Water Online Group

ArcGIS Online provides an extensive compilation of maps from all over the world. It is a digital encyclopedia of maps. Within ArcGIS Online, a group for World Water Online was created.

At the time of writing, the group has a global water information map, including the variables precipitation, discharge and flood stage. The map shows global information and it includes the Mexican databases (Figure 4.10).

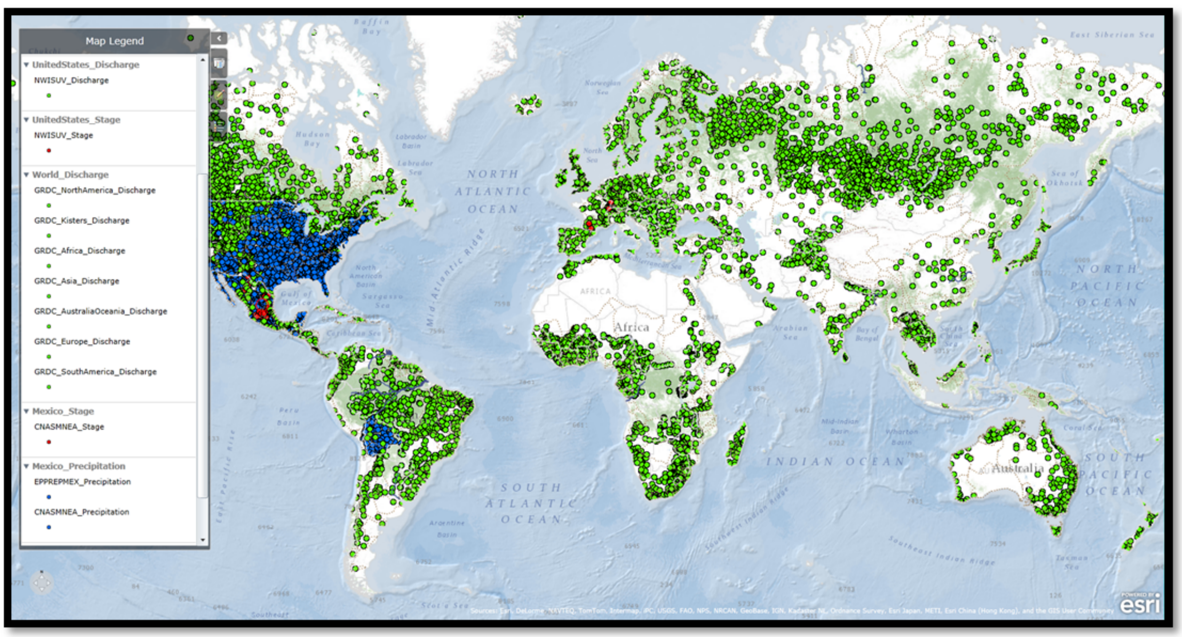

Figure 4.10: Water Information for the Global Map in World Water Online.

Beside Mexican water information, the map has discharge data from the Global Runoff Data Centre (GRDC) for the U.S.A. It also contains precipitation and flood stage data from the United States Geologic Survey (USGS).

4.2.1 Web Services Maps

There are four maps for the Mexican web services in ArcGIS Online: EMA's meteorological data, EMA's flood stage, the EPPREPMEX system and the BANDAS dataset. The maps can be accessed through the World Water Online group (Figure 4.11).

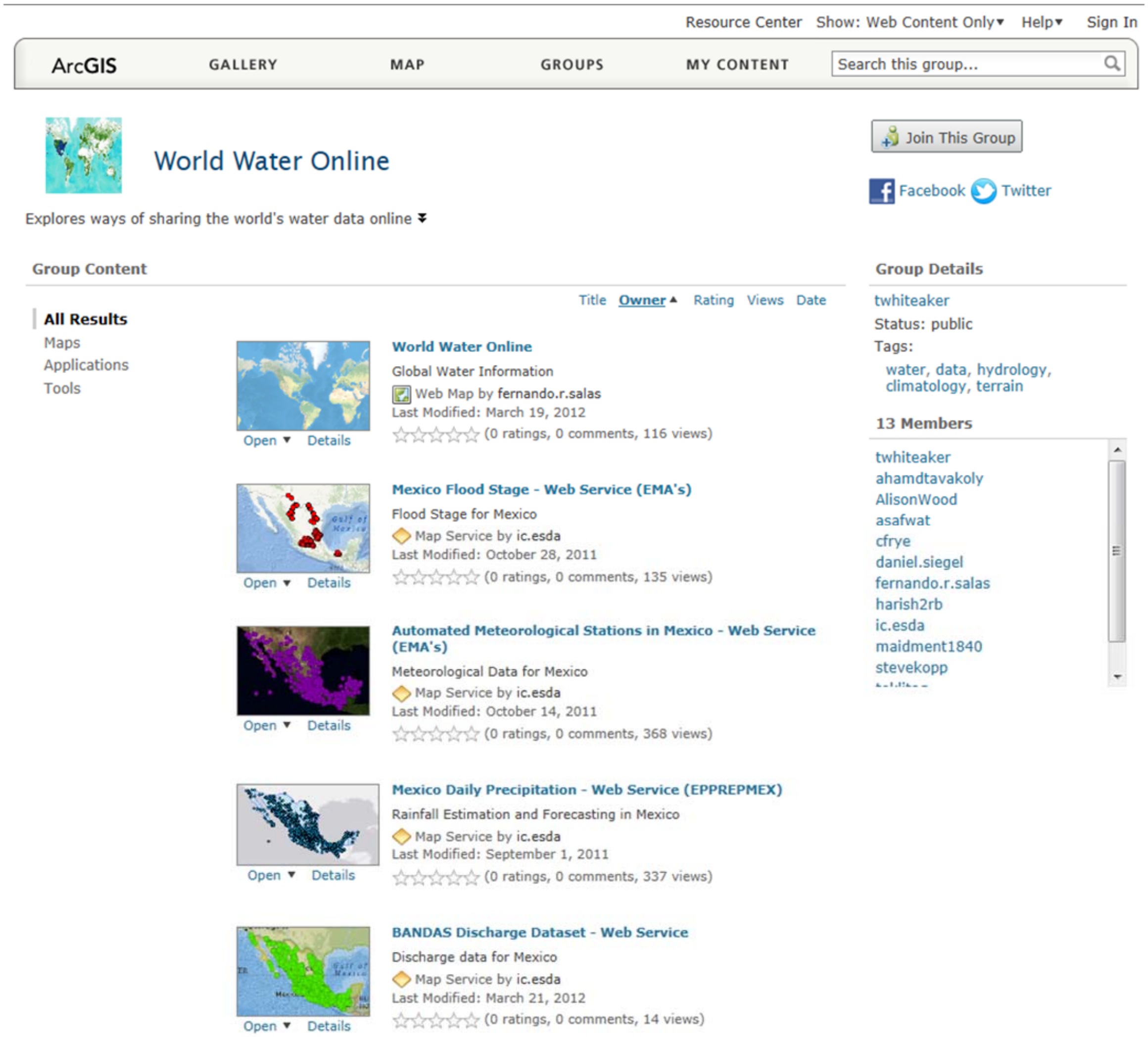

Figure 4.11: Map Web Services for Mexican Data within World Water Online Group.

4.2.2 Real Time Maps

There are two real time maps using the Mexican data from the databases. The maps are updated automatically and they display the latest values of precipitation and flood stage respectively.

The precipitation map (Figure 4.12) shows the latest daily precipitation value from the EPPREPMEX system. The map uses graduated symbols for the precipitation depth. The virtual stations with values equal to zero are not displayed.

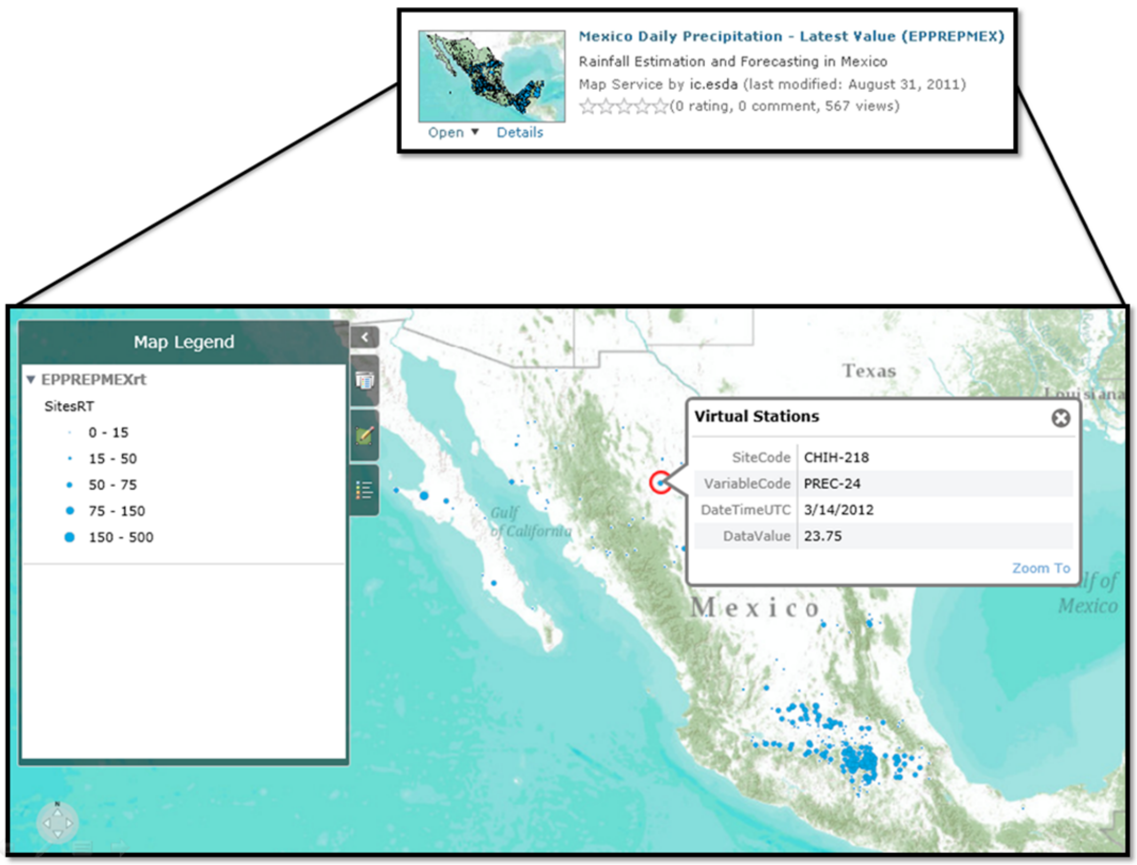

Figure 4.12: Latest-Value Precipitation Map for Mexico within World Water Online.

The flood stage map shows the latest value recorded in the EMA's network. The measured water depth in the rivers and the time when it occurred can be obtained by clicking on each individual station (Figure 4.13).

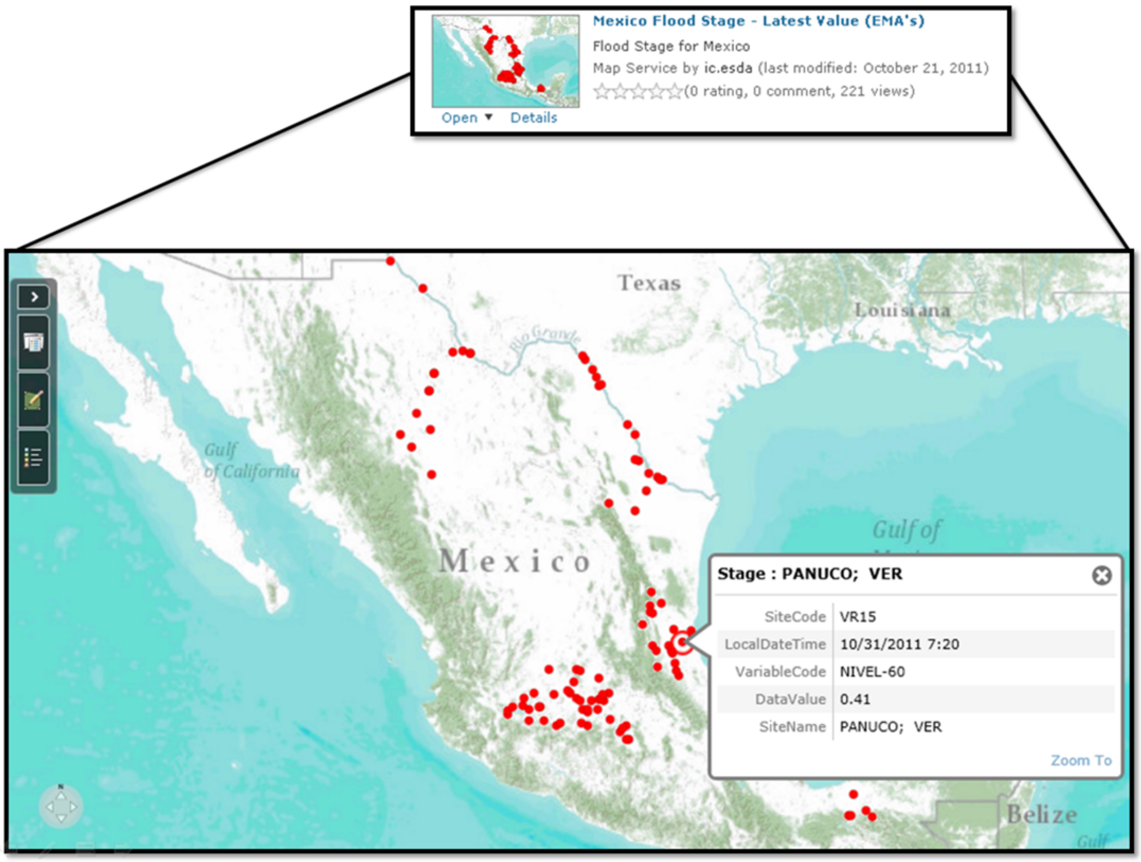

Figure 4.13: Latest-Value Flood Stage Map for Mexico within World Water Online.

4.3 PRECIPITATION MAP

The elevation-corrected precipitation map for Mexico is shown in Figure 4.14. The map displays the spatial variation of precipitation across the country, from the deserts and semi-desert regions in the north to the humid southern regions.

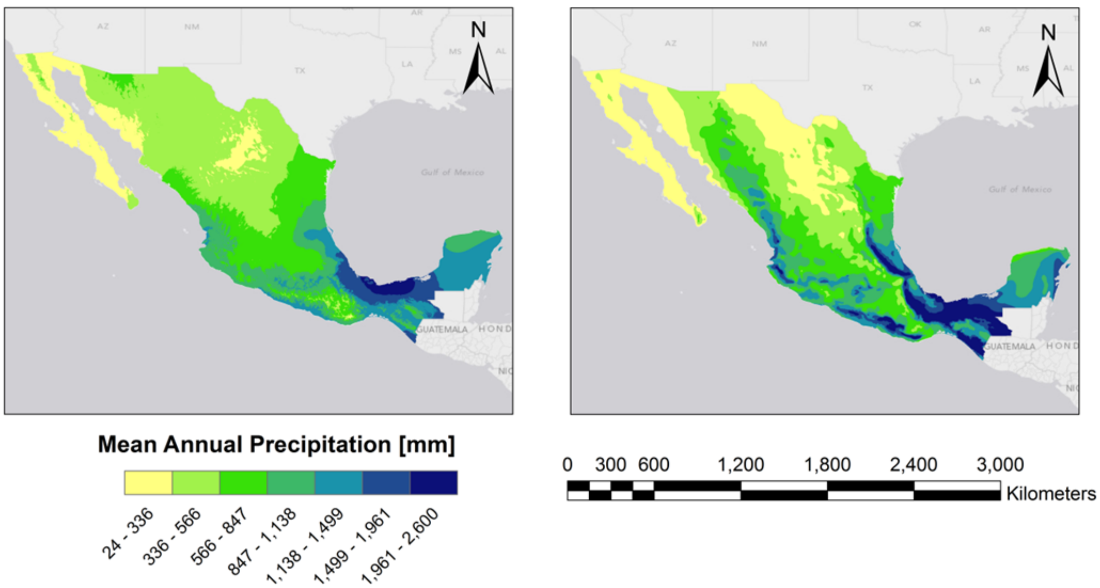

Figure 4.14: Comparison Between Interpolated Precipitation Map for the Period 1981 – 2000 (left) and the Official Mexican Precipitation Map from INEGI (right).

The precipitation map created with the methodology proposed (left), matches the spatial distribution of precipitation from INEGI (right). Due the limited stations available, the precipitation map created does not capture the areas with rainfall peaks or valleys, it smoothes over the differences. Compared to the official map, rainfall is underestimated for high precipitation areas and overestimated for arid areas. The map created shows a smoother transition between zones than the official map.

The standard error plot is shown in Figure 4.15. The error was computed for the geographic interpolation at sea level, which is in addition to the error induced through the elevation-precipitation regression plots.

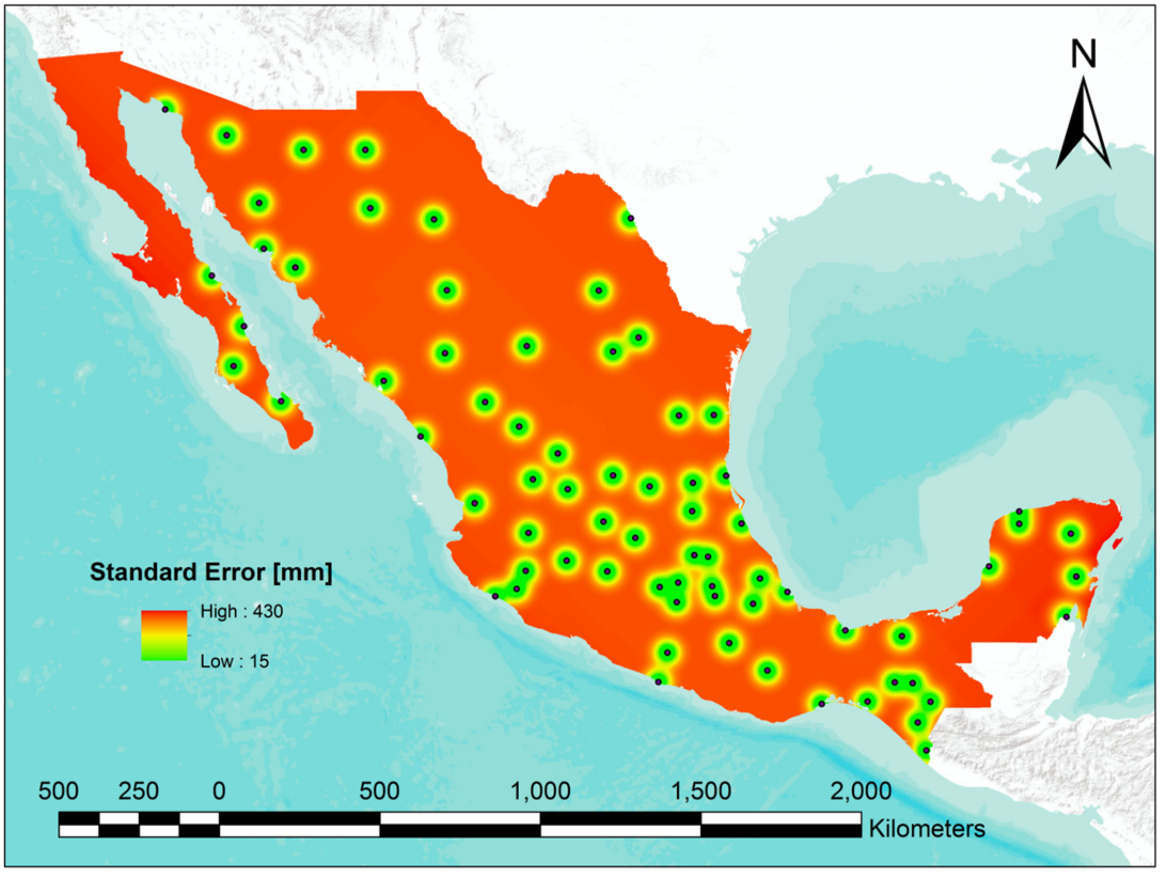

Figure 4.15: Standard Error Due to Kriging Interpolation at Sea Level.

The plot shows that the error could be significant in some areas. The stations' density across Mexico should be improved in order to generate better precipitation maps.

4.4 Runoff Weighted Hydro Basemap

The mean annual runoff in the stream network is selected to identify and symbolize the main rivers in the hydrologic region. The runoff value is used to determine the cartographic line width (Figure 4.16); the resulting map is a quick and valuable visualization of the drainage system in the region.

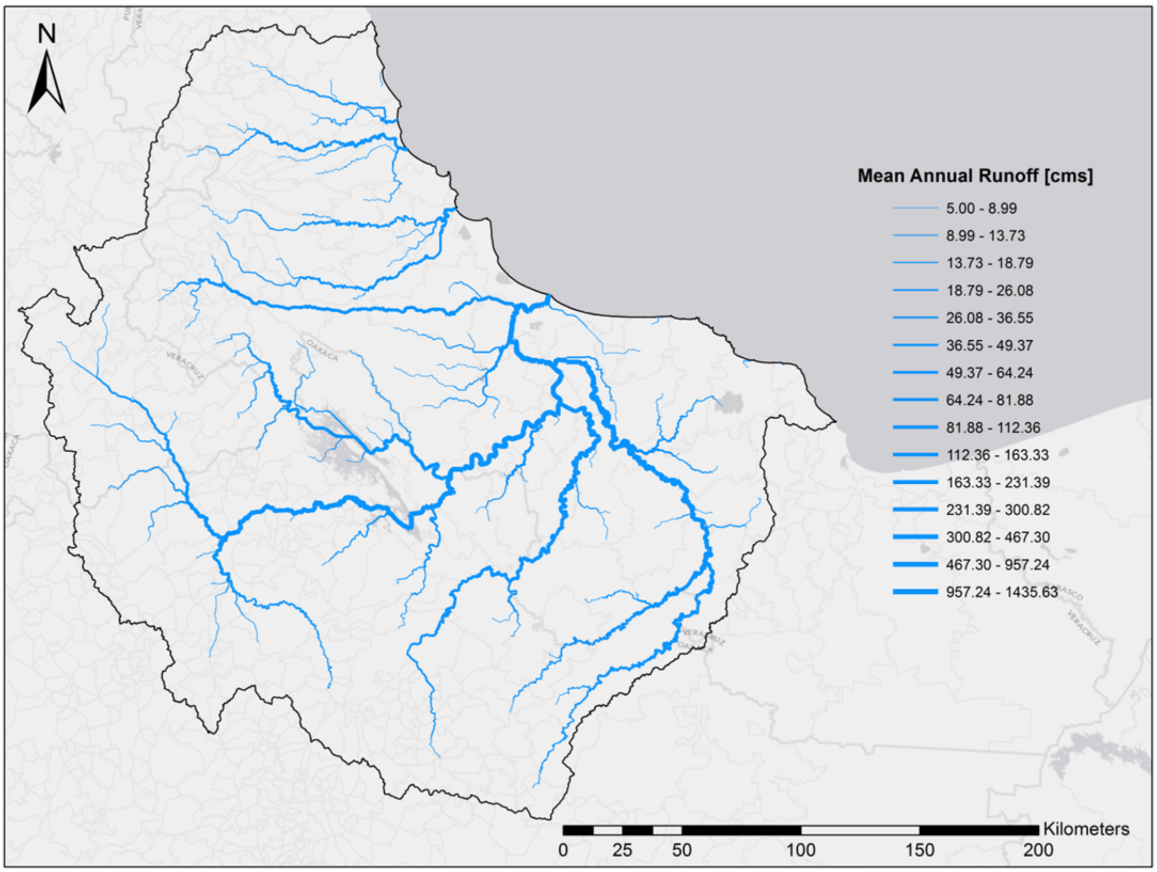

Figure 4.16: Runoff-Weighted Hydro Basemap for Hydrologic Region 28.

The comparison between the gaged CONAGUA values and the mean annual runoff values founded with this methodology is presented in Table 4.2. The standard error is 181 cms.

Table 4.2: Comparison between Gauged and Computed Mean Annual Runoff.

Station Number	Station Name	Mean Annual Runoff (CONAGUA)	Mean Annual Runoff (Methodology)
28188	EL ZETAL	3.48	19.09
28030	ACTOPAN II	45.69	26.06
28108	EL NARANJILLO	19.06	51.98
28111	IDOLOS	24.15	14.17
28003	CARDEL	61.33	58.79
28134	JALCOMULCO	76.96	45.56
28125	CARRIZAL	69.66	48.08
28133	AMATITLA II	82.38	18.79
28040	EL TEJAR	22.85	48.78
28039	PASO DEL TORO	59.17	41.95
28069	CAPULINES	99.14	42.60
28136	GARRO	71.34	196.68
28025	LAUCHAPAN	125.85	34.05
28153	LA CEIBILLA	65.69	335.32
28014	PAPALOAPAN	65.03	635.18
28015	CUATOTOLAPAN	78.48	274.76
28001	SAN JUAN EVANGELISTA	85.67	221.20

The average difference between the recorded and the computed mean annual runoff is 99.2 cms. The values are highly different for stations influenced by dams, such as for example, the Papaloapan station (28014). The flow in the region is diverted for agricultural and water supply purposes. The mean annual runoff computed with the methodology would be the one measured in the natural streams without anthropogenic abstractions.

4.5 DYNAMIC HYDRO BASEMAP

The information from INEGI's Hydrographic Network 2.0 was used to build a scale-dependent map (Figure 4.17). The map dynamically changes its display content depending on the zoom level used. The map represents a complete integration of hydrographic features through national, regional and local scales.

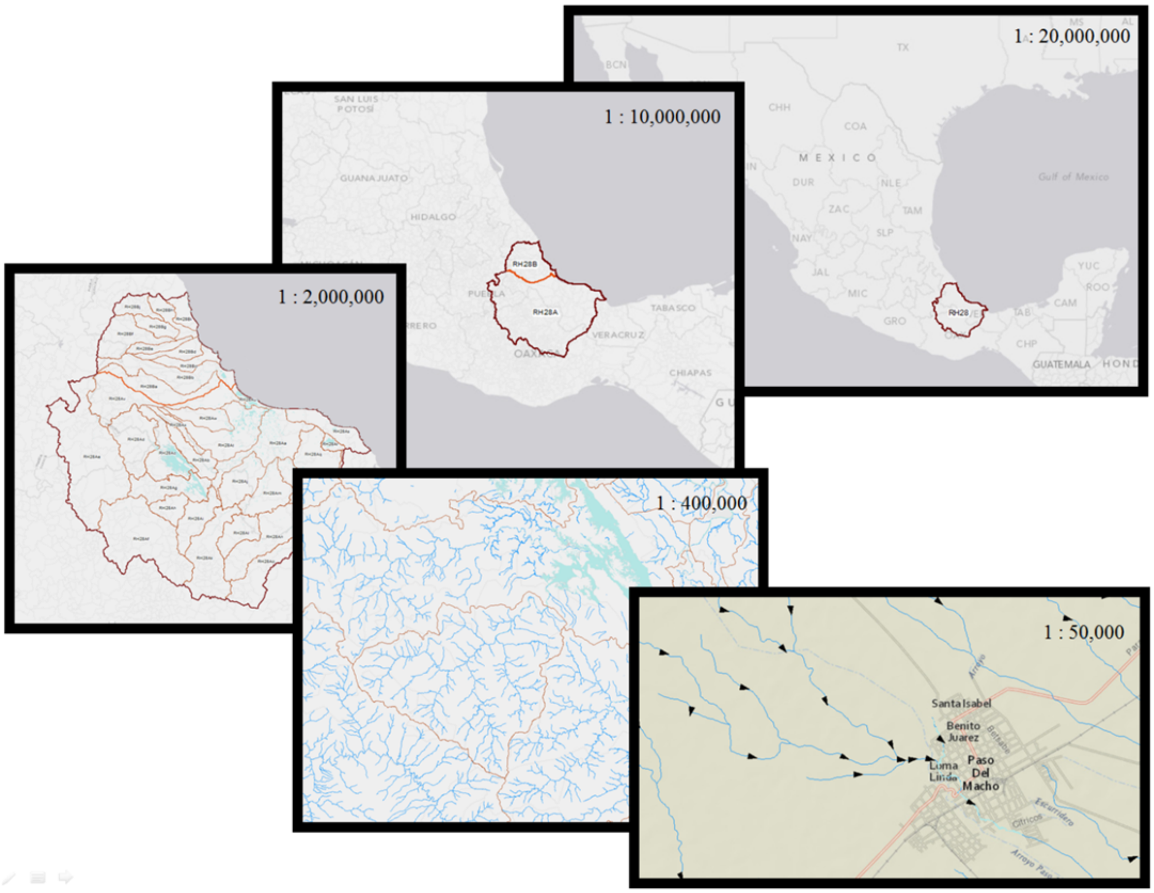

Figure 4.17: Screenshots for Selected Scale Ranges from the Dynamic Hydro Basemap of Hydrologic Region 28.

Chapter 5: Conclusions

5.1 Mexican-HIS

The hydrologic observations from Mexico are successfully integrated into a single system, which conglomerates and publishes the data from different sources and datasets as part of a global system, World Water Online.

The system uses the CUAHSI-HIS WaterOneFlow web services and ODM database structure. Each recorded value follows CUAHSI-HIS standards, improving the storing and sharing processes of hydrologic data in the country.

The use of the CUAHSI-HIS standard platform unifies the querying and accessing methods for the data. The methods are applicable for all the databases and all variables within the system: they are independent from data providers.

Additionally, there are two maps that display the latest value recorded in the system. The maps are for precipitation and flood stage variables respectively; they provide synthesized information of the current conditions, identifying spatial and temporal variations or tracking extreme events.

The Mexican-HIS system has no precedent in the nation; it improves the efficiency of discovering and accessing water data. It is a feasible system that helps the institutions in charge of water information to manage and provide access to the public in general.

5.2 World Water Online

World Water Online is emerging as a global system of water information. It is the integration of spatial and temporal hydrologic observations with engineering models and analysis. It provides access to water data at global, regional and local scales.

The Mexican-HIS case is a subset of the global information; it serves as an example for other countries and water agencies of what can be achieved. It is an encouraging application case, in which individual efforts are added together in order to continue building World Water Online.

5.3 PRECIPITATION-RUNOFF ANALYSIS

The Mexican-HIS data within World Water Online is used in a Precipitation-Runoff analysis. A precipitation map for Mexico is presented. The map considers the precipitation correction due to terrain elevation, and it is a source of information for the spatial variation of precipitation across the country.

The Precipitation-Runoff analysis is performed for hydrologic region 28; the stream network is extracted from the terrain. Precipitation and discharge data is correlated and mean stream flow rate is estimated for each river reach.

The standard error for mean annual runoff is 181 cms and it can be improved taken into account additional factors (as they become available) such as infiltration and evapotranspiration. Anthropogenic abstractions influence the analysis and they should be included. The computed mean annual runoff is valuable because it provides values for ungauged creeks. This information improves our understanding of the hydrology in the region.

5.4 HYDRO BASEMAPS

The hydrographic information for Mexico is integrated through hydro basemaps. The hydro basemaps condense hydrologic information through different scales.

Two hydro basemaps are created for hydrologic region 28. The first one dynamically changes its contents depending on the zoom level; it provides helpful hydrographic information from national to local scale. The second hydro basemap uses the discharge information of rivers and streams, highlighting the rivers with more flow; the map shows the trajectory of water from the hydrologic divide to the ocean.

5.5 Areas of Future Research

The Mexican-HIS within World Water Online represents a great improvement for water information in the country. Future research should consider extending the databases. Historic data for EMA´s network and EPPREPMEX system can be loaded; the BANDAS dataset can be ingested with the missing stations.

A close relationship with SEMARNAT and CONAGUA should be achieved, complementing the Mexican-HIS with additional information, such as water quality parameters and groundwater data.

The systems should be migrated to servers in Mexico, giving the maintenance responsibility to the institutions that manage the data. In this scenario, all water participants from academic, government and research centers will be working in an integrated way, combining efforts and providing solutions.

World Water Online needs to continue increasing the number of participating countries in the global system; its success relies on the individual efforts of each country and each country's willingness to share hydrologic information. World Water Online can be used to build transboundary water information datasets, approved and agreed upon by riparian countries, providing a base for allocating water and minimizing disputes.

The Precipitation-Runoff analysis can be complemented with evapotranspiration and infiltration data. The effect of anthropogenic works in river reaches should be estimated and the precipitation map can be improved with topographic aspect corrections.

Appendix: EMA's Mean Precipitation 1981 - 2000

Code	Name/State	Latitude	Longitude	Altitude [masl]	Precipitation [mm]
76061	Puerto Peñasco; Son.	31° 19' 52"	-113° 33' 12"	61	159.1
76113	Altar; Son.	30° 42' 52"	-111° 50' 05"	397	603.9
76118	Pilares de Nacozari; Son.	30° 22'	-109° 41'	1040	557.9
76122	Nuevo Casas Grandes; Chih.	30° 22'	-107° 57'	1467.5	325.4
76160	Hermosillo; Son.	29° 04' 42"	-110° 55' 48"	211.3	287.7
76220	Temosachic; Chih.	28° 57'	-107° 49'	1932	465.9
76225	Chihuahua; Chih.	28° 40' 14.2"	-106° 01' 49.5"	1372.08	385.7
76243	Piedras Negras; Coah.	28° 42'	-100° 31'	249.65	520
76253	Santa Rosalía; B.C.S	27° 17'	-112° 15'	82	78.1
76256	Empalme; Son.	27° 57'	-110° 48'	12	232.3
76258	Cd. Obregón; Son.	27° 29'	-109° 55'	38.39	289.1
76305	Loreto; B.C.S	26° 01'	-111° 20' 50"	6.76	140.6
76323	Hidalgo del Parral; Chih.	26° 55'	-105° 40'	1785	450.3
76342	Monclova; Coah.	26° 54' 30"	-101° 25' 21"	615.4	298.8
76373	Tepehuanes; Dgo.	25° 20' 16"	-105° 43' 23"	1810.2	474.4

76382	Torreón; Coah.	25° 31' 11"	-103° 25' 52"	1123	205.8
76390	Saltillo; Coah.	25° 22' 35"	-101° 01'	1789.83	432.4
76393	Monterrey; N.L	25° 44' 01"	-100° 18' 17"	515	545.5
76402	Cd. Constitución B.C.S	25° 00' 35"	-111° 38' 48"	48.26	140.6
76405	La Paz; B.C.S	24° 07'	-110° 19'	18.5	178.4
76412	Culiacán; Sin.	24° 38' 05"	-107° 26' 26"	38.58	690.1
76423	Durango; Dgo.	24° 05' 41"	-104° 35' 59"	1871.6	448.8
76458	Mazatlán; Sin.	23° 13'	-106° 24' 38"	2.83	800.2
76471	Sombrerete; Zac.	23° 28'	-103° 39'	2351	576.2
76491	Cd. Victoria; Tamps.	23° 44' 52"	-99° 10' 18"	335.97	912.1
76499	Soto la Marina; Tamps.	23° 46'	-98° 12'	21	751.9
76519	Colotlán; Jal.	22° 06' 26"	-103° 16' 04"	1736	595.1
76525	Zacatecas; Zac.	22° 46' 42"	-102° 33' 59"	2612	510.4
76539	San Luis Potosí; S.L.P.	22° 12' 27"	-101° 01' 20"	1883.23	367.4
76543	Tamuin; S.L.P.	22° 01' 00'	-98° 47' 01"	23	907.5
76548	Tampico; Tamps.	22° 12' 00"	-97° 51' 22"	25.45	937.8
76556	Tepic; Nay.	21° 29' 21"	-104° 53' 35"	915	1235.8
76571	Aguascalientes; Ags.	21° 51' 12"	-102° 17' 29"	1877	500.9
76577	Guanajuato; Gto.	21° 00' 20"	-101° 17' 08"	1999.4	711.1

76581	Río Verde; S.L.P	21° 55' 17"	-99° 59' 47"	983.5	524
76585	Matlapa; S.L.P	21° 16' 36"	-98° 48' 20"	133.25	1791.9
76593	Progreso; Yuc.	21° 16' 33"	-89° 39' 14"	2	923.9
76612	Guadalajara; Jal.	20° 42' 36"	-103° 23' 24"	1551	942.9
76625	Querétaro; Qro.	20° 35'	-100° 24'	1880.5	638.3
76632	Pachuca; Hgo.	20° 07' 42"	-98° 44' 51"	2425	362.3
76634	Tulancingo; Hgo.	20° 05' 3.24"	-98° 21' 26.85"	2213.54	491.4
76640	Tuxpan; Ver.	20° 57' 35"	-97° 25' 08"	10	1368.2
76644	Mérida Aeropuerto; Yuc.	20° 57'	-89° 39'	11	923.9
76647	Valladolid; Yuc.	20° 41' 24"	-88° 12' 15"	26.6	1141.2
76654	Manzanillo; Col.	19° 02' 39"	-104° 19' 6.99"	3.41	974.6
76656	Cd. Guzmán; Jal.	19° 43 ' 50"	-103° 27' 53"	1515	722
76658	Colima; Col.	19° 14' 32"	-103° 43' 13"	444.48	1014.4
76662	Zamora; Mich.	19° 59'	-102° 19'	1561.85	725.4
76665	Morelia; Mich.	19° 42'	-101° 11'	1912.7	756.2
76675	Toluca; Méx.	19° 17' 28"	-99° 42' 51"	2726	777
76680	México Central; D.F	19° 24' 13"	-99° 11' 46"	2308.6	846.1
76683	Tlaxcala; Tlax.	19° 18' 43"	-98° 14' 39"	2247.95	845.2
76685	Puebla; Pue.	19° 03'	-98° 10'	2179	816.5
76687	Jalapa; Ver.	19° 30' 43"	-96° 54' 14"	1360	1432
76692	Veracruz; Ver.	19° 09' 40'	-96° 08' 13"	19.45	1564
76695	Campeche; Camp.	19° 50'	-90° 30'	5	1186.2

76698	Felipe Carrillo Puerto; Qroo.	19° 34'	-88° 03'	10	1461
76726	Cuernavaca; Mor.	18° 53' 32"	-99° 14'	1618	1201.5
76737	Orizaba; Ver.	18° 51'	-97° 06'	1259	2193.3
76741	Coatzacoalcos; Ver.	18° 08' 24.39"	-94° 31' 05.04"	16	2577.1
76743	Villahermosa; Tab.	17° 59"	-92° 56'	6.5	2481.3
76750	Chetumal; Qroo.	18° 29' 51"	-88° 19' 35"	8.98	1179.7
76762	Chilpancingo; Gro.	17° 33'	-99° 30'	1264.5	773.2
76773	Huajuapan de León; Oax.	17° 48'	-97° 46'	1680	703.9
76775	Oaxaca; Oax.	17° 04'	-96° 42'	1519	600.1
76805	Acapulco; Gro.	16° 45' 47"	-99° 44' 56"	3.12	1465.5
76833	Salina Cruz; Oax.	16° 10' 15"	-95° 10' 45"	2.2	1122.3
76840	Arriaga; Chis.	16° 14' 28"	-93° 53' 51"	48.5	1452.8
76843	Tuxtla Gutiérrez; Chis.	16° 45'	-93° 08'	570	865.3
76845	Sn Cristobal de las Casas; Chis.	16° 44'	-92° 38'	2115.3	1047.3
76848	Comitán; Chis.	16° 14'	-92° 08'	1606.9	957.2
76855	Puerto Ángel; Oax.	15° 40' 24"	-92° 29' 10"	43	1025.4
76903	Tapachula; Chis.	14° 55' 15"	-92° 15'	118.05	2237.7

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Vita

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